IDRC-234e

Irrigated Forestry in Arid and Semi-Arid Lands: A Synthesis

F.B. Armitage

85-6160/

The International Development Research Centre is a public corporation created by the Parliament of Canada in 1970 to support research designed to adapt science and technology to the needs of developing countries. The Centre's activity is concentrated in five sectors: agriculture, food and nutrition sciences; health sciences; information sciences; social sciences; and communications. IDRC is financed solely by the Parliament of Canada; its policies, however, are set by an international Board of Governors. The Centre's headquarters are in Ottawa, Canada. Regional offices are located in Africa, Asia, Latin America, and the Middle East.

©International Development Research Centre 1985
Postal Address: Box 8500, Ottawa, Canada K1G 3H9
Head Office: 60 Queen Street, Ottawa, Ontario

Armitage, F.B.

IDRC-234e

Irrigated forestry in arid and semi-arid lands : a synthesis. Ottawa, Ont., IDRC, 1985. 160 p. : ill.

/Forestry/, /forest production/, /irrigation/, /arid zone/, /semi-arid zone/ — /irrigation systems/, /plantations/, /economic aspects/, /bibliography.

UDC: 63.0:631.67

ISBN: 0-88936-432-X

Microfiche edition available.

Il exist également une édition française de cette publication.

IDRC-234e

Irrigated Forestry in Arid and Semi-Arid Lands: A Synthesis

F.B. Armitage

Abstract

Use of irrigation in forest plantations in many arid and semi-arid areas since the 1860s has demonstrated in some cases a potential for high wood yields and thus for countering the depletion of meagre natural wood resources, with related environmental degradation, that stems from population increases. This synthesis is aimed at enhancing irrigated forestry through an examination of past experience, the range of inputs required, and the benefits of integrating tree plantations with irrigated agriculture. It reviews the potential for irrigated forest plantations and provides a checklist of economic, sociological, and technical criteria needed to guide decisions as to the feasibility of such developments. Actions to be covered in the planning, implementation, and operational phases of irrigated forest plantations are indicated as are illustrative production levels and research needs. The closing chapters review the approaches in economic analysis, management, and planning.

Résumé

L'irrigation est une technique employée dans beaucoup de plantations forestières des régions arides et semi-arides depuis les années 1860. Dans certains cas, cette technique a montré qu'elle pouvait accroître le rendement des forêts et ainsi contrer l'épuisement des maigres ressources forestières naturelles attribuable à la croissance démographique, tout comme la dégradation de l'environnement qui l'accompagne. La présente synthèse vise à améliorer la foresterie irriguée par un examen de l'expérience acquise, des facteurs de production et des avantages inhérents de l'association des plantations d'arbres à l'agriculture. Elle aborde aussi le potentiel des plantations forestières irriguées et offre une liste des critères économiques, sociaux et techniques à employer pour décider de la faisabilité d'établissement de telles plantations. Elle précise les étapes de la planification, de la mise en œuvre et de l'exploitation de ces plantations et donne une idée de leur rendement et des besoins de recherche dans ce domaine. Les derniers chapitres portent sur les méthodes utilisées en analyse économique, en gestion et en planification.

Resumen

El uso de la irrigación en las plantaciones forestales de muchas áreas áridas y semiáridas a partir de 1860 ha demostrado en algunos casos el potencial para obtener altos rendimientos de madera y para contrarrestar, así, el agotamiento de recursos madereros naturales escasos y la degradación ambiental relacionada que deriva de aumentos poblacionales. Esta síntesis tiene por objeto ampliar la silvicultura irrigada mediante un análisis de la experiencia anterior, de la gama de insumos requeridos y de los beneficios de integrar plantaciones forestales con agricultura irrigada. También reseña el potencial de las plantaciones forestales irrigadas y ofrece una lista de los criterios económicos, sociológicos y técnicos que se requiren para orientar las decisiones en cuanto a la factibilidad de tales desarrollos. Se indican las acciones que deben realizarse en las etapas de planificación, ejecución y operación de las plantaciones forestales irrigadas, así como los niveles de producción ilustrativos y las necesidades de investigación. Los capítulos finales reseñan los enfoques adoptados en el análisis económico, el manejo y la planificación.

Contents

Foreword 7

Acknowledgments 9

Executive Summary 11
- Introduction 11
- The arid zone environment 11
- Irrigated forest plantation experience 12
- Some basic concepts 13
- Irrigation systems 13
- Assessment of needs and potentialities 14
- Development of irrigated plantations 15
- Implementation and production 16
- Economics of irrigated plantations 17
- Organization and management 18
- Planning 18

1. Introduction 19

2. The Arid Zone Environment 21
- Environmental characteristics 21
  - Climate 21
    - Arid climates 21
    - Semi-arid climates 22
    - Subhumid and humid climates 22
    - Climatic indices 22
  - Geomorphology 24
  - Soils 24
  - Hydrology and water resources 25
  - Drainage and salinity 26
  - Vegetation 27
- Land use and the need for irrigation 28

3. Irrigated Forest Plantation Experience 29
- Regional and country accounts 31
  - South Asia and the Middle East 31
    - Pakistan 31
    - India 34
    - Iraq 35
    - Kuwait 35

United Arab Emirates 36
Other Middle Eastern countries 37
The Mediterranean region 37
Tunisia 38
Algeria 38
Italy 38
Egypt 39
Turkey 39
Israel 39
East, West, and Southern Africa 40
Sudan 40
Kenya 43
Mali 44
Niger 46
Nigeria 49
Sénégal 49
Zimbabwe 51
North America 52
United States of America 52
South and Central America 53
Australia 54
Conclusion 55

4. Some Basic Concepts 57
Plant–soil–atmospheric water relationships 57
Irrigation and soil properties 58
Irrigation and topography 59
Hydrological implications of irrigation 60

5. Irrigation Systems 61
Gravity systems 61
Sprinkler systems 63
Localized systems 64
Special irrigation systems and devices 65
Rainwater harvesting: runoff farming 68
Criteria for selection of irrigation systems 69

6. Assessment of Needs and Potentialities 71
Population and socioeconomic trends 71
Need for tree products 71
Land and water for wood production 73
Technical feasibility 76
Water for irrigation 76
Quality 76
Quantity 78
Tree species for irrigation 80
Tolerance of waterlogging and salinity 83
Root systems 84
Tree growth and wood quality 86
Socioeconomic feasibility 87
Decision criteria for forest plantation development 90

7. Development of Irrigated Plantations **91**
Forms and scale of irrigated plantations **91**
Land use and tenure **91**
Physical and ecological survey **93**
Assessment and development of water resources **94**
Design of irrigated production systems **96**
Irrigation systems and water regimes **96**
Silvicultural systems and regimes **99**

8. Implementation and Production **103**
Installation of irrigation and drainage systems **103**
Tree establishment and tending **104**
Nursery production **104**
Preparation of planting site: spacing **105**
Plantation establishment **106**
Fertilization **108**
Weeding and cleaning **109**
Stand tending: thinning and pruning **110**
Water management and use **111**
Rates and methods of application **111**
Efficiency of water use: water losses **114**
Maintenance of irrigation and drainage systems **115**
Problems related to irrigation **117**
Waterlogging and salinity **117**
Root-system growth disorders and diseases **118**
Birds, insects, and animals **120**
Environmental and human-health implications of irrigation **121**
Growth and yields **122**
South Asia and the Middle East **122**
India **122**
Iraq **122**
Israel **122**
Kuwait **123**
Pakistan **123**
Africa **123**
Niger **123**
Nigeria **124**
Sudan **124**
Zimbabwe **124**
General **125**
Research needs **126**

9. Economics of Irrigated Plantations **129**
Needs, opportunities, and the need for evaluation **129**
Economic analysis and evaluation **130**

10. Organization and Management **137**

11. Planning **143**

Appendix 1. Tree species used under irrigation **147**

Appendix 2. Provisional rating of salt tolerance of trees and shrubs in Kuwait **149**

Appendix 3. Successful tree species under saline irrigation at Eilat, Israel **150**

Appendix 4. Species tolerant of interrupted irrigation at Khartoum, Sudan **150**

Bibliography **151**
Key sources **151**
References **152**

Foreword

In arid and semi-arid lands, water is one of the most limiting factors for plant growth and rainfed agriculture has low and unpredictable yields. Thus irrigation, where it is possible, has become a common practice. Equally, in forestry, natural vegetation and rainfed plantations have low annual increments that cannot meet the increasing needs of the local communities for fuelwood, building materials, and other products. This net deficit of forest biomass production leads to a depletion of the natural resource followed by the unavoidable desertification process, affecting human life and the environment.

Over the past decades, research has focused on the introduction of fast-growing tree species and on planting techniques adapted to arid and semi-arid conditions. Fast-growing species of pines, eucalypts, and others were experimented with in many countries with variable success. In an effort to avoid the depletion of the soil by such species and to widen their use, emphasis in the last decade has been on multipurpose and nitrogen-fixing trees that can provide wood, fodder, and protection and yet maintain or increase the soil fertility. Despite these efforts, the performance achieved by the trees has been limited by the low levels of available water.

Several of the arid and semi-arid areas of the world are crossed by major rivers, but agricultural irrigation schemes often do not use the water resource to its full potential and water is being wasted. At the same time, irrigation has been geared mainly toward food-crop production and seldom to forest tree crops — with the major exception of Pakistan and to a lesser extent India and the Sudan.

In 1974, the International Development Research Centre (IDRC) initiated a research project on irrigated forestry plantations to study the effect of irrigation on tree crops. The first scientific results were controversial, mixing spectacular success of some species with failure of others. The economic results also appeared to be controversial because high costs were involved in pure forestry plantations whereas plantations associated with agricultural crops and those using excess or waste water were promising.

To establish the potential of irrigated plantations in arid and semi-arid areas of the developing world with a special focus on Africa, F.B. Armitage, who has had considerable forestry experience in the arid and semi-arid areas, prepared a state-of-the-art review under a contract with IDRC. Helped by the staff of IDRC's forestry program, he gathered the information available on the topic, met several scientists in the field, and prepared a draft document. On the basis of peer reviews, the author revised the draft, which then served as a discussion paper for a meeting of a small group of experts and representatives of countries and donor agencies. This meeting, initiated by IDRC and hosted by the Commonwealth Forestry Institute (CFI) in Oxford, U.K., was held in March 1985. In preparation for publication, the document

was then revised a second time by the author to incorporate additional comments and issues raised during the Oxford meeting.

This book is neither a manual nor is it a simple state-of-the-art volume. It is intended to serve as a source of information and as a general guide for decision-makers and managers in the field of irrigated forestry. It is also expected that the book will lead to a series of interactions and to cooperation between scientists and developers and between institutions at regional and international levels. The information provided on the experience in various countries and the voluminous bibliography will constitute a starting point for such networking initiatives.

IDRC wishes to thank J. Spears and his colleagues from the World Bank, Washington, DC, USA, and P.J. Wood of the International Council for Research in Agroforestry, Nairobi, Kenya, for their valuable contribution for the peer review. Equally valuable was the contribution of the participants to the Oxford meeting — J. Burley, CFI; R.F. Fishwick, the World Bank; O. Hamel, Centre technique forestier tropical, Nogent-sur-Marne, France (posted to Niamey, Niger); W. Howard, Overseas Development Administration, London, U.K.; T.H. Mather, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy; M.I. Sheik, Pakistan Forestry Institute, Peshawar, Pakistan; and P.J. Wood. The comments by B. Ben Salem of FAO conveyed to the meeting were highly appreciated. We also thank CFI for hosting the meeting.

H. Zandstra
Director, Agriculture, Food and
Nutrition Sciences Division,
International Development Research Centre

Acknowledgments

The compilation of this synthesis has entailed the support and assistance of many people representing a range of functions in several institutions. I wish to acknowledge in particular the ready support of Mr Karim Oka of the International Development Research Centre (IDRC) under whose direction the review and synthesis was done; the staffs of the IDRC library in Ottawa and of the library of the Commonwealth Forestry Institute, Oxford, U.K., and the generosity of several members of the staff of the World Bank, Washington, DC, USA, but particularly of Mr Jean Gorse, in providing information on projects supported by that institution. The synthesis would hardly have been possible without the series of land and water publications of the Food and Agriculture Organization of the United Nations in Rome, Italy.

Fuelwood and fodder are needed in arid environments: A goat browsing near Dongola in the Sudan.

Executive Summary

Introduction

Irrigation to enhance the production of food and esthetic values has been practiced in arid and semi-arid lands from ancient times. Its use for forest production is more recent. Irrigation is a complex activity, and successful practice requires inputs from a variety of specializations. This synthesis is intended to facilitate forestry applications of irrigation technology by indicating the specialized inputs needed and sources in the forestry and agricultural literature. Its purpose is also to indicate to irrigationists and agriculturalists the feasibility and the potential benefits of integrating tree plantation with agricultural cropping, to encourage such development in appropriate instances, and to stimulate the formulation of the necessary guidelines.

The Arid Zone Environment

Irrigation is practiced where natural water supply is inadequate to support plant production. Thus, its importance is greatest in arid or semi-arid areas having low, variable rainfall, high incident radiation, high summer or year-round temperature and evaporation rates, low atmospheric humidity, and frequently strong winds. Indices are used to classify climate in relation to plant growth and for the assessment, planning, and conduct of plant production systems, including irrigation.

Arid-zone geomorphology includes characteristics such as mountain massifs that change through sharp angular breaks in slope to associated pediments, alluvial fans, outwash plains, flats, and depressions that strongly influence the distribution of soil-forming materials and water. Abrupt deposition of materials transported by infrequent runoff events results in coarse deposits along ravines and the formation of gravel bars and beds. Windblown sand forms dunes or sand sheets on virtually any land form.

The climate greatly affects soil formation, most of the processes involved being progressively slower or impeded with increasing aridity. The breakdown of parent material is speeded up in the high and variable temperature conditions. However, vegetation and organic material have minimal influences. Illuviation and the redistribution and recrystallization of soluble salts through leaching are virtually confined to depressions where occasional runoff accumulates. The soils are low in nutrients. Silty deposits in depressions are often saline and alkaline crusts and gravelly desert plains are common. As aridity decreases, the soils become more developed, deeper, and more leached and calcareous pans occur at progressively greater depths. Poorly drained depressions in particular are characterized by alkaline or sodic soils.

The hydrology and water resources of arid zones have characteristics related

directly to their climates. The quantities of precipitation available for groundwater replenishment are meagre so that aquifers are either fed by rivers that rise in more humid zones or contain very old water. With increasing aridity, much of the water available for irrigation is saline.

Soil and water salinity problems are more widespread and acute in arid than in temperate areas. They affect one-third of the 200 million ha of irrigated land in the world. They arise as a result of high evaporation rates, precipitation of salts in marine sediments, direct contamination of underground water by the sea, from fossil brines, or through deposits of airborne salts. According to their chemical characteristics and variations in pH and electrical conductivity, these soils can be saline, sodic, or saline-sodic. The high sodium content of the latter two can seriously affect soil physical properties.

The vegetation of arid areas varies from none to moderately sparse and its distribution is sensitive to site factors. It has features that manifest the adaptation of dry-area species to such environments. Although reasonably robust, such vegetation can be heavily degraded by excessive cutting, grazing, and browsing. Regeneration is slow.

Concentrations of burgeoning population, usually beside major rivers, give rise to pronounced local needs for food, fuelwood, and fodder. As a result, the natural vegetation is depleted, desertification often ensues, and irrigation using surface or groundwater is practiced to achieve several-fold increases in food production and, in some cases, tree products as well.

Irrigated Forest Plantation Experience

Good data as to the extent of irrigated forest plantations are not available. The first major plantings began in 1864 in the Indus Valley and, by 1969, they represented 0.8–0.9% of the area under irrigation. In the Gezira irrigation project in the Sudan, they represented 0.43% of the irrigated area in 1967. Very large areas of irrigated poplar and willow plantations exist in Argentina. It is unlikely that irrigated plantations approach 1% of the overall area under irrigation in spite of sometimes extreme wood deficits.

Irrigated tree plantations are commonly integrated with agriculture, particularly in the form of shelterbelts. For this reason, they often share with agriculture problems of waterlogging and associated soil and water salinity, particularly when they occupy small uncultivated areas that are virtually dumping grounds for excess irrigation water. Plantation production is thus often appreciably less than it could be, or it declines with the advancing age of irrigation schemes. Other reasons include the use of suboptimal species, provenances, or mixtures; inadequate cultural methods; plantation management regimes that do not ensure optimal occupation of the site; excessive, inadequate, or irregular watering; invasion by weeds; inadequate system maintenance; and declining site fertility.

High or very high rates of volume production have been demonstrated to result from combinations of all or most of the following features: good research and development followed by realistic deduction; thorough analysis of local soil, water, sociologic, and economic conditions; use of appropriate irrigation methods; sound project design, implementation, and management; and high motivation and proper training of all growers and staff concerned.

Some Basic Concepts

A knowledge of plant–soil–atmospheric water relationships is basic to understanding irrigation practice. Movement of water within the soil is subject to mechanical and molecular forces and is affected by soil infiltration capacity. Reduction of soil water below field capacity leads eventually to levels referred to as the incipient and then the permanent wilting percentages, which are affected by soil physical properties. Water uptake by a plant depends on the characteristics and dynamic status of water within it, water potential at the root surface, and the efficiency of the root system. The driving force for the ascent of water within the plant results from evaporation from the leaf surfaces, which causes movement of water to them from the xylem cells (tracheids in gymnosperms), which are fed by the root system. Evaporation from leaf surfaces is affected by atmospheric conditions. Climatic data can be used to predict soil moisture condition, potential evaporation, evapotranspiration, and thus soil moisture surplus and deficiency.

Soil structure, which can be modified by cultural practice, and texture influence the permeability and water-holding capacity of soils and thus the quantities and frequencies of irrigation. Soil chemical and physical features are closely bound up with each other and with the movement of solutes. It is possible to determine the best combination of irrigation water amount and its salt content and to manipulate both through the watering regimes used and by fertilization.

Topography affects soil-forming processes and the hydrology of an area, and influences selection of irrigation sites and methods.

Irrigation implies major changes to the hydrology of an area and measures must be taken to offset any that are unfavourable, e.g., waterlogging and salinization, to preserve site fertility.

Irrigation Systems

A variety of irrigation systems has been developed to meet the range of conditions that exist. They must meet three basic requirements: a sustained economic return, minimal loss of water during conveyance and application, and prevention of site degradation. Selection of method is made in relation to the specific operational situation under consideration.

There are five principal types of gravity systems: the wild flooding, border check, basin, furrow, and corrugation methods. Wild flooding is the least efficient and is seldom used except for pastures. The border check method requires a relatively large flow of water. Basin irrigation is the simplest and most easily controlled, and the most useful for heavy soils and when leaching is required to cure soil salinity. Furrow irrigation is frequently used in forestry; however, it does not permit sensitive control of water use and can induce root malformation. Corrugation irrigation has no application in forestry. All these systems require careful site preparation.

Sprinkler systems are available in areas of irregular topography where land grading is not feasible or where rapid applications of moderate amounts of water are required. Applications for forestry are limited by crop heights and costs. They have the disadvantage of requiring water under pressure.

Localized systems (trickle or drip irrigation methods) are particularly useful in conjunction with low yielding water points and with saline water. They have the disadvantage that the small-bore pipes easily become clogged.

Special irrigation systems include methods to reduce water losses through control of evaporation; methods of temporary watering during the establishment phase to assist root systems to reach permanently moist areas of the soil; and subirrigation and the use of underground moisture barriers, which have little or no application in field forestry.

Rainwater harvesting systems have been used in arid areas for centuries to direct infrequent runoff or dew into the rooting zones of crops, including tree crops, or to assist groundwater recharge.

Criteria for system selection usually relate to features concerning topography and land grading; soil characteristics; quantity and quality of water; amelioration of soil salinity; biological aspects, such as root-system development and disease; ease of management and control; degree of sophistication, motivation, and training of labour; and investment, operating, and maintenance costs.

Assessment of Needs and Potentialities

Recent increases and concentrations of population, especially in arid and semi-arid lands, have depleted natural resources and strained the basic means of producing them. One of these is water, supplies of which have rapidly been approached and sometimes overtaken by demand. Innovative and intensive measures have been taken to increase or conserve water supplies. Demands for trees and wood for many purposes have increased in step with population increases, particularly where wood is a major form of domestic fuel. Indeed, in some documented instances, it is difficult to foresee how the demand, which averages 0.5–1.2 m^3/person per year, can ever be met, so low are rates of natural production and so degraded the natural ecosystems. Dung and agricultural residues are among the substitutes used for fuel. There is great potential for many of the needs to be met by integrating tree growing with agriculture. However, instances are likely to occur where the development of blocks of uniform plantations is warranted.

The need for land and water for irrigated wood production leads to conflicts and competition with agriculture, except apparently when municipal and industrial effluents are to be used. The conflicts can be partially resolved by integrating agriculture and forestry production. The land and water available are sometimes offered because they are of inferior quality: if so, they must be realistically assessed as to quality and extent in relation to the level of production required. Water supplies for irrigation should be reliable, economically acceptable in cost, and, although trees are able to withstand irregular watering better than agricultural crops, regularly available.

Irrigation water quality affects plant growth and its characteristics in respect of salt, ionic, trace element, biocide, and suspended solids content should, accordingly, be known, particularly when municipal effluents are to be used. The irrigation water requirements of tree species under specific growth conditions are usually imperfectly known and require research. Procedures using local climatic and soil data and the water-need characteristics of species have been developed for predicting theoretical water requirements of agricultural crops. They await wider adaptation to irrigated forestry. However, the use of empirical methods is likely to prove more effective in practice. It is desirable to increase the scale of application of the concept of multi-purpose use of water, i.e., reuse of this scarce, costly commodity whenever feasible.

A wide range of species yielding many product types under a variety of conditions has been documented. A short list of superior performers emerges in relation to

substantial ranges of criteria. In most regions, there is room for introduction, testing, and selection of improved species, provenances, and cultivars.

Tree species vary in their tolerance of reduced soil aeration and also in their tolerance of waterlogging and salinity. The mechanisms by which salts affect growth are known and are used experimentally to test the response of plant growth to salinity.

Irrigation modifies root system morphology because it increases soil moisture and can thus reduce aeration. Thus root systems readily become shallow or, in furrow irrigation, oriented linearly along the ridges between channels. This can lead to reduced growth and windthrow.

The meagre information available on the effects of irrigation on wood quality hardly permits generalization. However, unfavourable influences have not been reported.

Economic analyses have been reported for irrigated plantation schemes in several countries. They all indicate that, subject to needed changes being made in technical or managerial inputs, irrigated plantation forestry under the conditions described is economically feasible and potentially at least as attractive as some agricultural cropping alternatives. Among the most important inputs influencing success are the management ones. The analyses mentioned here do not always take full cognizance of unquantified costs and benefits, nor have they always been accompanied by what are currently recognized as adequate sociological analyses.

A checklist of decision criteria emerges in relation to the feasibility of irrigated plantations in one form or another in any particular instance: the demand for tree products; proven need for irrigation; availability of land and water of acceptable quality, quantity, and reliability; technical irrigation and silvicultural feasibility; lack of unacceptable environmental implications; social feasibility (land tenure, cultural environment, and existence or potential for managerial skills); and economic feasibility.

Development of Irrigated Plantations

The often relatively low financial returns and risks entailed in perennial forestry crops, particularly large-scale uniform plantations, renders integration with agriculture an attractive alternative in many instances: overall returns are not unduly delayed and the tree crop returns enhance the financial results of agricultural irrigation schemes. However, the integration of the two must be of a coherent nature.

Land use and tenure factors are usually profoundly important for the success of irrigation schemes because they bear directly on the interests of affected people whose support in the development must accordingly be encouraged.

Detailed physical and ecological surveys are necessary for the design and implementation of irrigation schemes. Physiographic, geological, topographical, infrastructural, and tenurial features are mapped at relatively small scales. Soil surveys may be undertaken at three successive, more detailed stages, i.e., a preinvestment or reconnaissance stage, a semidetailed feasibility stage, and a detailed design and execution stage. Soil moisture and groundwater characteristics would be included.

Irrigation water supplies and their development must be properly assessed to provide a basis for design and implementation. Parameters of particular importance are quantity (adequacy), seasonal fluctuation, reliability, quality, possible future

changes, and costs. Technologies (and very often separate agencies as well) are available for the development and management of supplies from both surface and groundwater sources. As with the required soil surveys, foresters do not normally have the expertise to undertake water-supply assessments, development, or management alone.

The success of irrigation schemes depends greatly on irrigation systems and watering regimes designed to ensure optimum economic returns, economy in use of water, and sustainability of site productivity for an indefinite time. Achievement of these tenets requires a planning process that takes account of the pertinent economic, social, physical, chemical, and biological factors. It necessitates inputs by specialists in several fields, selection of the most appropriate irrigation method and water supply and delivery systems consonant with the crops' water requirements, and provision of an adequate drainage system. The design should be sufficiently flexible to permit the moderate adjustments that would inevitably be required. The design package would include comprehensive operating guidelines and instructions. Project silvicultural systems and regimes would also be designed after full analysis of pertinent aspects. They would provide for appropriate degrees of integration of tree and agricultural crops, to the benefit of all concerned. The crop types would be the most straightforward to manage in relation to the outputs required, unnecessary complications such as mixtures being avoided.

Implementation and Production

Efficient long-term operation depends on care and correctness in the installation of irrigation systems. High standards are desirable in the construction of water supply and drainage systems to reduce water losses and subsequent maintenance costs and in land grading and furrow construction to ensure evenness of water distribution. They are also required in the production and handling of nursery stock, preparation of plantation sites, and in planting or sowing. Planting arrangement and density must accord with the needs of the species used and the plantation management regimes to be applied. Important benefits can accrue from application of inorganic fertilizers or of gypsum or manure, or both, to ameliorate soil or water salinity. Timely cleaning is necessary for optimal growth of direct-seeded plantations. Irrigation encourages copious weed growth that must be controlled if it is not to reduce crop performance. Thinning and pruning should be applied at predetermined times and intensities to ensure optimal yields and stem quality consonant with full occupation of the site by the crop.

Water-use management has the primary objectives of efficient water use, optimizing yields, and maintenance of site fertility. Water requirements of the crop are carefully determined and frequently checked, rainfall being taken into account. The amounts applied are recorded and the whole system is continuously refined by monitoring based on an integrated series of applied research and testing trials. To parallel these, climatic information is collected and groundwater fluctuations and quality, soil physical and chemical properties, irrigation water quality and availability, irrigation efficiency, and water losses are monitored in relation to crop growth so that adjustments can be made as and where required. Regular maintenance of water supply and distribution arrangements is necessary for efficient system operation.

The most important problems of irrigation are those associated with waterlogging due to the deliberate application of excessive quantities of water and to

seepage, which, in the absence of underground drainage, raise the water table and cause secondary salinity — which can also be caused by the use of saline irrigation water. These problems can be prevented by the inclusion of appropriate measures in design, implementation, and operation: reclamation once they have occurred is costly and can destroy productivity.

Root malformation can be associated with the furrow or localized irrigation methods and root diseases may be caused by waterlogging, i.e., excessive irrigation, or by irregular watering. Crop damage due to birds associated with tree plantations sometimes occurs; in some cases, it may be offset by benefits. Insect and animal damage is usually local and readily controllable.

Possible environmental implications of a potentially hazardous nature associated with irrigation include soil and groundwater pollution, particularly when municipal and industrial effluents are used, human parasites and disease vectors that spend at least part of their life cycle in stagnant water, and unforeseen physical effects of waterlogging or measures to counteract it. The effect of large-scale irrigation on local climate appears not to be measurable.

A wide range of volume growth rates has been reported for irrigated plantations. The two principal conclusions to be drawn from them are, first, that potential production is often high to very high although, second, these potentials are seldom reached because of unfavourable factors, most of which appear to be controllable.

The priority area for research and development is in respect of the water requirements of irrigated tree crops. Other important topics requiring research and development would expand the array of species and provenances suitable for irrigated plantations; further develop and improve irrigation systems; improve methods of reclamation of areas affected by salinity; further develop silvicultural regimes for irrigated plantations; expand available information on growth and yield and on such forest management tools as tree and stand growth tables; elucidate the environmental effects of using municipal and other effluents; and establish methods to deal with undesirable effects.

Economics of Irrigated Plantations

Irrigated tree plantations vary in scale and scope from the few trees that might be planted by a farmer to large enterprises undertaken by governments or corporations. They are all undertaken to meet specific physical or esthetic needs, some may be based opportunistically on resources of land or water that are surplus to other enterprises or become available as a result of other activities, and some may be deliberate primary-production ventures. All of them, at some stage, would be subject to some form of economic analysis to identify and assess needs or opportunities, to compare alternatives so that the most favourable can be selected, to assess the progress and results of existing projects or of one or more of their components, or to compare these with alternative strategies.

The analyses mentioned involve the comparison of costs and benefits, using one of four discounted measures that are applicable to perennial crops, more particularly if the cost and benefit streams of the various alternatives are of different shapes or their time spans dissimilar. The methods are applicable to either financial or economic analyses, for which an appropriate discount rate is selected from four available alternatives. The precision of analysis depends, of course, on good input and output data.

It is notable that a review of several World Bank irrigation projects by one of the authorities cited indicated that the major problems of design and implementation are inappropriate technology, inadequate infrastructure and support systems, failure to appreciate the social environments of projects, and problems due to weak management and administration.

Organization and Management

A project cannot succeed without an appropriate organizational structure and effective management. The manner in which a project organization is structured to carry out the range of managerial, operational, and maintenance functions entailed will depend on the nature and size of the project and the social, institutional, and technical circumstances that bear on it. A fund of well documented experience exists to guide the formulation of the organizational structure needed for management in each case. Effectiveness of the latter function depends on clearly defined program policies and objectives, adequate delegation of authority, particularly to the project level itself, well designed systems for irrigation and forest production as well as for management and monitoring, adequate financing, and an effective legal framework for distribution and control of water supplies. Management training of staff at all levels is an important ingredient for success, yet is often neglected.

Planning

The planning or plan-formulation process entails the establishment of objectives and activities to be undertaken, the selection of criteria for the evaluation of alternative designs or strategies, the collection of information for the comparison of alternatives, and the selection of the optimum plan. The process is facilitated in irrigation projects by the existence of a policy for the orderly development of water resources.

Planning and management are integral parts of the continuum known as the planning cycle: plan formulation–implementation–evaluation–reformulation, with budgeting, programing and monitoring as elements included in the second and third of these steps. Good management is made possible by a good plan that is kept current by the application of this cycle.

1. Introduction

Irrigation is known from archaeological, written, and folklore records to have been practiced from ancient times in the Old World. Its primary purpose was to produce food from annual vegetable and cereal crops as well as to grow perennial vines and trees that produced fruits, such as grapes, olives, and dates. Its use was extended to the growing of flowering shrubs, such as the rose and jasmin, and trees for ornament, shade, and shelter, for all of which the gardens and tree-lined roads of ancient cities such as Babylon and the more recent Granada in Spain and Rome of Nero's time were famous. Irrigation was practiced for these purposes when plants were grown in dry conditions outside their natural rainfed environments or the need arose to enhance yields. In time, the ranges of food crop, ornamental, and shade plants widened. This has been the case particularly in recent centuries with the introduction of corn, avocados, guavas, the honey locust (*Robinia pseudacacia*), and many other plants from the New World to Europe, Africa, the Middle East, and Asia.

The irrigation of trees for wood production is a relatively recent development, largely because natural supplies were sufficient to meet needs when populations were of light or moderate density and local concentrations small before the population increases that have characterized the present century. Grazing and browsing over the centuries by the flocks and herds of relatively small populations gradually reduced the areas of natural woody vegetation in many parts of the world, albeit without causing widespread shortages.

During the last 50–100 years and in most cases more nearly the former than the latter, the situation has changed radically. Populations have been doubling every 15 years or even less in many countries. Many people are poorer. The overall demand for a wide range of commodities, including wood, has increased. Natural stocks of wood have been depleted quickly. In the face of priorities for the production of food and because tree crops often take several years to become productive, production of wood from both the natural woodlands and plantations in the dry areas of the world has frequently not matched demand. Serious deficit situations have developed rapidly and are now too often the normal condition. They are most marked in arid and semi-arid areas, particularly in the vicinities of towns and cities, concentrations of population along perennial rivers, or in irrigated agricultural colonies. In many such areas, populations are still growing rapidly. The deficits relate particularly to wood as a staple domestic fuel and for building poles. Other important needs are for fodder for camels, goats, sheep, and cattle, shade and shelter, and the ameliorative effects of shelterbelts in cultivated areas. These trends are most marked in arid and semi-arid zones where environments for plant growth are usually harsh.

In response to the high demand–inadequate supply situations that have arisen, wood-production systems have been intensified over several decades and are still being developed in this way. They have become increasingly characterized by the

introduction, testing, selection, and genetic improvement of fast-growing tree species, provenances, cultivars, land races, and clones; sophistication of seed and nursery supply systems; intensive site preparation and cultural methods, including fertilization; and, where possible, irrigation. The first development of irrigated plantations on any scale began in the arid and semi-arid Indus Basin of what is now Pakistan in 1864 to meet the specific need for fuel for operation of the railways and to produce high quality hardwood lumber. Irrigated plantation schemes subsequently became locally important in other countries, e.g., Italy, Turkey, the Sudan, and India. They are now widespread throughout the arid and semi-arid zones of all continents of the world, in areas of both winter and summer rainfall. Usually, they do not dominate agricultural cropping, which is the primary user of irrigation waters, but tend increasingly to be integrated with it in various ways. At the same time, traditional systems for growing trees, e.g., date and other fruit trees, in conjunction with annual crops, as in the Mediterranean climate areas of North Africa, continue to be used and to be developed in various ways.

Tree irrigation schemes vary in scale from large concentrated block plantations or smaller scattered ones, through a variety of designs involving lines or small groups of trees, to individual trees. They are grown for a wide range of single or multiple purposes by agencies that vary from government departments and corporations to individual small farmers. Although growing trees under irrigation is often successful, particularly in the early stages, ventures of this kind frequently fail, or yields decline after an initial phase of high productivity, for one or more of several reasons.

Irrigation is a complex activity. Sustained production requires inputs from several scientific and technical specializations. Irrigated tree plantation calls for expertise not only from foresters but also from irrigation specialists and, particularly where tree growing is integrated with agricultural cropping, from agronomists as well. In any but the simplest schemes, economic and sociological inputs are also needed in the planning phase and at intervals subsequently. Often, the advice of soils and plant-protection specialists is also required. There is a tendency for foresters, perhaps in ignorance of the complexities with which they are dealing, or in face of opportunities that may seem too fleeting to allow any avoidable delay, to act without inputs from an adequate range of other specializations in developing irrigation initiatives. As a result, the outcome is frequently less than optimal if not actual failure. Accordingly, the primary purpose of this synthesis is to support foresters in their schemes to develop irrigated tree plantations by indicating the complexity of the subject and providing a source document that would assist them in identifying the nature and sources of the specialized inputs they might require. At the same time, the document is intended to bring to the attention of agriculturalists and irrigationists the fact that soundly planned and managed integration of tree plantation with annual-crop production can present important opportunities to enhance the financial and economic success of irrigation schemes. The synthesis is not intended as a technical guideline for the practice of irrigation but rather to be a precursor to the formulation of guidelines appropriate to specific sets of conditions and applications.

The topics of organization and management and planning are included because proper applications of these phases, although critical to project success, are often deficient and nearly always inadequately covered in the basic training of field foresters.

Although the literature used for the synthesis is believed to represent substantially that which is available for most of the countries covered, it reflects the apparently scanty coverage that exists for irrigated forestry in Latin America and the difficulty of accessing that for China and Russia.

2. The Arid Zone Environment

The potential for production of agricultural and tree crops under irrigation is particularly important in arid and semi-arid lands because, although people and their flocks and herds live there, the natural environmental conditions restrict rainfed plant production to low levels. At the same time, conditions of climate and soil exist in such areas that, when they are combined with artificially applied water, can result in very high levels of production from selected, concentrated areas. The environmental and general land-use characteristics of arid and semi-arid lands are briefly reviewed in this chapter as a prelude to the consideration in succeeding chapters of how the potential for irrigation development might be exploited.

The terms "arid" and "semi-arid" are used here to denote areas where environmental conditions either do not support rainfed crops or are sufficiently erratic to render production under such conditions marginal or unreliable. The term "irrigation" is used in relation to practices by which water is transported by artificial means from a point source and applied to the soil in a specific area with the object of optimizing the growth of a managed crop. This definition excludes the age-old, but still practiced, technologies known as rainwater harvesting or runoff agriculture, which are reviewed briefly in chapter 5.

Environmental Characteristics

Climate

Irrigation is practiced where the water required for crop production is not adequately supplied by natural means and must therefore be supplemented artificially. Irrigation is thus closely bound up with climate, and a good understanding of the relationship between the two is necessary for successful design and operation of the process. This may be illustrated by the fact that the seasonal pattern of demand for supplemental watering in areas of Mediterranean climate is different from that in zones with summer rainfall. Also, rainfall patterns and amounts affect both the quantities of supplemental water required and those that are available for the purpose. Climatic data form an essential part of the basis for calculation of irrigation dosages and schedules.

Four broad climatic types, within each of which there is a range of detailed climatic patterns, may be considered in relation to the need for irrigation: *arid*, *semi-arid*, *subhumid*, and *humid*. It is in the first two that irrigation is of most interest.

Arid climates

Arid climates are defined (e.g., McGinnies et al. 1968, Fuchs 1973a, Jones et al. 1981) as those in which crops cannot be regularly raised without irrigation. They are

generally characterized by low sporadic rainfall of great variability over time and space, averaging 200 mm or less annually, which, when it arrives, can be of high intensity, resulting in devastating floods. Levels of incident radiation are high as are temperatures, at least in summer, and they are subject to high annual and seasonal variations. Evaporation rates are also high, particularly during the growing season. Atmospheric humidity is low a short distance inland from the sea. Strong winds with frequent dust- and sandstorms usually occur. Certain of these features are sometimes mutually compensating as for example in the Rajasthan Desert in India where high atmospheric dust content over lengthy periods at certain times of the year reduces radiation with consequent increase in relative humidity.

Semi-arid climates

Semi-arid climates have characteristics that are even more variable than those of arid regions although, as implied, conditions do not preclude plant growth to the same degree. Fuchs (1973a) labels as semi-arid all those regions in which rainfall deficiency calls for irrigation during part of the growing season. Dry farming is possible; however, its productivity is low and restricted to a few drought-resistant species.

Several climatological entities can be included within the pragmatically defined semi-arid zone: the tropical *savanna climate*, the subtropical *Mediterranean climate*, and the *steppe climate*. These embrace wide differences and variations in precipitation (in all cases up to about 750 mm/year) and its distribution, temperatures, and their annual patterns.

The *savanna climate*, which occurs over most of the area covered by the intertropical convergence zone, is warm enough to support plant growth throughout the year, with the highest temperatures occurring in the growing season.

The *Mediterranean climate* has a mild, well defined winter during which most of the rainfall occurs. The summer is typically hot and rainless. This type of climate occurs throughout the world at the fringes between the tropical and temperate zones. Nonirrigated agriculture is based on winter crops such as wheat, whereas summer crops are restricted to a few species with very short growing seasons or plants with root systems that reach deep moist layers of the soil. Rainfall occurrence is unpredictable and annual amounts highly variable.

The *steppe climate*, which comprises many variations, occupies larger areas than any other climatic category. It forms the transition between arid climates on the one hand, and the savanna, Mediterranean, or temperate subhumid types on the other. As with Mediterranean and savanna climates, solar radiation and summer temperatures are favourable for high production.

Subhumid and humid climates

In subhumid climates, where rainfall varies widely from year to year, large-scale irrigation is usually avoided by planting drought-resistant species that tolerate the relatively short dry periods and unpredictable droughts. Irrigation is of little relevance in humid climates.

Climatic indices

Major parts of the arid and semi-arid zones fall within the tropics and subtropics where their climates are influenced to a greater or lesser extent by variations in the latitudinal position of the intertropical convergence zone — the area of low atmospheric pressure where northern and southern hemisphere winds converge. The

seasonal position of this convergence zone corresponds with the monthly rainfall maxima in many arid areas on the fringes of the tropics and the extent of its movement away from the equator each year determines to a great extent the rainfall that they experience (Jones et al. 1981). The foregoing factors interact with the three features generally recognized as the principal causes of aridity (Reitan and Green 1968). They are, first, separation of an area, for example, by high mountain barriers, from major oceanic sources of moisture; second, the formation of dry, stable, air masses that resist convective currents; and, third, lack of occurrence of storm systems.

The need for a framework of reference for climate, particularly in relation to crop and vegetation management, has resulted in the development of a number of climate-classification systems or indices — although it is always understood that one climate grades into the next by continuous transition. The sequence of development of classification systems was outlined by Thornthwaite and Hare (1955) who described the results of early work, notably that by Grisebach, who in 1866 published the earliest significant map of vegetation regions, by Linsser on the effects of temperature on phenology and of rainfall on vegetation that led him to divide the world into climatic zones, and by Koppen whose climatic classification, first published in 1900 with a major revision in 1931, is still in use among geographers. The essence of Koppen's work was that plants might be used as instruments that integrate climatic elements. This integrative approach underlay the classification of climate proposed by Thornthwaite in 1948 (see Thornthwaite and Hare 1955), in which the principal integrative parameter used was potential evapotranspiration (PET), a measure of climatic potential derived from the thermal regime.

Thornthwaite's system is important because, by taking into account solar radiation, dissipation of water vapour in the atmosphere, the vegetative cover and its capacity to reflect incident radiation, and the nature and moisture status of the soil, and by making adjustments for variations in day length to bring about the close relationship that then exists between temperature and evapotranspiration, it permits the computation of PET for any place whose latitude is known and for which temperature records are available.

Among the parameters that are predictable through the use of Thornthwaite's system are *moisture surplus* and *moisture deficit*. These, together with annual PET, are combined in Thornthwaite's *moisture index*, which is the basis for his division of the world into ecologically distinct moisture provinces or zones. Refinements and elaborations based on this approach were used by Meigs (1953) for classifying and mapping arid-zone climates and for the development by the United Nations Educational, Scientific and Cultural Organization (Unesco) and the Food and Agriculture Organization of the United Nations (FAO) of a scheme for bioclimate mapping of the Mediterranean zone (Reitan and Green 1968).

Several systems are used to depict climatic parameters in an integrated manner as well as numerically through the use of diagrams not much larger than postage stamps. One of the more widely used of these is the system of "klimadiagrams" devised by Walter and Leith (1967). Another is the use of "ombrothermic" diagrams incorporated in the Unesco–FAO system for bioclimatic mapping.

Climatic classification systems and indices are important in the assessment of potential economic activity. Some are used as empirical guides in the conduct of such activity, e.g., rainfed and irrigated silviculture in parts of the Mediterranean zone of North Africa (Metro in Kaul 1970). Some are applied in the theoretical calculation of irrigation regimes, as discussed in chapter 6 in the section "Water for irrigation."

Synopses of the climates of dry lands would not be appropriate here. However, many good world, regional, and country accounts are available and synopses for the world's deserts are given by Reitan and Green (1968). Other broad area accounts are given in publications of the World Meteorological Organization (WMO). Kaul (1970) gives short descriptions for many countries. Examples of individual country and zonal accounts include that of Ashraf Ali (1971) for the Indus Plain of Pakistan and Satchell (1978) for the United Arab Emirates.

Geomorphology

The warm arid zones have certain typical landform features that have been caused or emphasized by climate over long periods. Landscape patterns such as mountain massifs, plains, pediments, deeply incised ravines, and drainage channels often display sharp changes in slope and topography and high degrees of angularity. At lower elevations, rivers traverse wide floodplains and are subject to periodic changes of course. Many of the landforms may be overlain by sand, in the form of either unstable dunes or sand sheets (Lustig 1968; Jones et al. 1981). Windblown sand may affect any type of relief (Dan 1973) and it often inundates cultivated and irrigated lands and canals (Wood 1977).

Other geomorphological features of particular relevance are those that influence soil formation and characteristics. Notable among these are the distribution of coarse and fine soil fractions as a result of transportation, reworking, and deposition by wind and water, and the periodic inundation of floodplains, beneficial effects of which are the replenishment of soil nutrients and organic materials and the leaching out of accumulated salts in the soil.

Soils

Climate has important influences on soil formation and soil characteristics. In arid areas, wind and occasional water erosion are severe so that gravelly desert plains, sand dunes, and sand sheets are prevalent. High diurnal temperature fluctuations speed up the disintegration of parent materials. On the other hand, the impacts of all other soil-forming influences are reduced by aridity and increase as humidity increases. This applies to the influence on soil formation of vegetation and the organic compounds associated with it; to the leaching and recrystallization at depth of soluble salts (e.g., gypsum and lime), and to the illuviation and movement down the soil profile of clay materials.

In gravelly desert plains, hard pans of gypsum or other salts are widespread. Saline soils also develop in silty deposits in depressions, particularly those that are poorly drained, due to capillary movement to the surface of saline groundwater.

In arid desert fringe areas, e.g., the arc of higher ground on the northeast, north, and northwest fringes of the Indus Plain in Pakistan, extensive loess belts often occur, and ecological conditions (particularly moisture) permit the development of a grass cover. A lime horizon frequently occurs at shallow depth but such soils are seldom markedly saline.

In semi-arid zones, the soils are more developed than in arid areas, there being a grass cover or, with increasing humidity, savanna. The soils are more developed, more highly leached, particularly in the A and B horizons, and the lime horizon, if present, is at greater depth. Fine-textured soils that crack when dry are widespread. With

decreasing aridity, good soil structure increasingly becomes a feature, the soils of the floodplains and depressions are relatively well developed and the poorly drained depressions are often characterized by alkaline soil. Where the climate becomes more markedly characterized by alternating wet and dry seasons, soil formation tends to be altogether more pronounced and advanced. Where natural drainage is impeded, as it is, for example, in the upper parts of the Indus Valley in Pakistan by a subterranean ridge, or where poor irrigation methods are used, silty or clayey plains sediments can become saline or alkaline.

The interrelationships between climate and soil formation in arid and semi-arid zones are described by Dan (1973) among others. Outline descriptions of the soils of areas of varying degrees of aridity across the southern Mediterranean region, the Middle East, and into Pakistan and India are given in Kaul (1970). Ali (1960) gives a brief account of the mainly alluvial soils of the Indus Plain.

Hydrology and water resources

In the arid zone, local groundwater usually supports irrigation of relatively small areas (Fuchs 1973a). Most of the irrigation water used is taken from large rivers that originate in areas of higher rainfall, e.g., the Nile in Sudan and Egypt, the Euphrates, Tigris, Indus, Ganges, Sénégal, and Niger. Knowledge of groundwater movement and recharge rates is vital, however, when groundwater is extracted, to ensure that, in the long term, extraction does not exceed replenishment, and to avoid serious damage such as saline-water intrusion.

Israel, with its underground water-carrier systems, provides a good example of stringent, scientific management and budgeting on a national scale for scarce water generated within or adjacent to the arid and semi-arid zone. Two-thirds of all the water used, for all purposes, is pumped from aquifers that, in addition to acting as sources of water, are also used for water storage, as conduits, for regulation of base flow by pumping from confined aquifers, and, because of their granular structure, as natural filters (Buras 1973a).

Replenishment of groundwater is strongly dependent on rainfall amount, intensity, and duration as well as on relief and the nature of the soil surface, which influence runoff. In the arid zone, runoff events, streamflow, and groundwater and soil moisture storage are more variable and less reliable than in temperate zones. Much of the rain that falls is dissipated by evaporation so that groundwater is replenished only locally by seepage from infrequent spates. This is why, in desert areas, bodies of fresh, comparatively young water are formed in the vicinity of rivers, where the infiltration rates through channel alluvium are high, whereas regional aquifers usually contain old brackish water — Simpson (1968) suggests as old as 10 000 years (Buras 1973a; Mandel 1973; Jones et al. 1981). In arid areas, groundwater is frequently used at rates that exceed recharge.

Two types of springs that occur in arid regions are of interest. The first includes the large perennial ones that form the outlets of calcium carbonate aquifers. Their existence is the result of the formation of solution channels by groundwater containing dissolved carbon dioxide and the progressive generation of flow channels leading water to one common outlet. The solution channels follow fractures related to tectonic activity (Jones et al. 1981).

The second type is represented by saline swamps in desert regions. These are maintained by aquifers, the water from which evaporates as soon as it appears at the

surface. In the centre of the swamp is a sterile region covered by salt encrustations surrounded by salt-resistant phreatophytes. Date palms are often grown on the fringes of such swamps, forming oases. Reasonably good quality water can be obtained from boreholes drilled some distance away, where salt content has not yet reached high levels (Mandel 1973).

In much of Asia and Africa, people have disturbed natural springs over long periods, e.g., by digging into them to get more water. In some cases, as in Algeria, such digging has been deep enough to disturb shallow, impervious sediments. As the spring flows, vegetation grows and sand accumulates to raise the outlet until it is large enough to absorb the spring discharge. As aridity increases, the number and discharges of natural springs usually decrease (Jones et al. 1981).

Although salinity is discussed in the next section, it is appropriate to note here that, in many parts of the arid and semi-arid world, all natural water that is available for irrigation is affected in some degree by salinity. Arar (1975) describes such conditions in Bahrain, Saudi Arabia, Kuwait, the Tagora area of the Libyan coastal plain, the United Arab Emirates, and the Yemen Arab Republic. Cointepas (1968) discusses similar phenomena in Tunisia, Satchell (1978) for the United Arab Emirates, and Firmin (1971) for Kuwait.

The hydrology of large tracts can be greatly affected by underground features that cannot be seen but that influence groundwater movement patterns. This is sometimes the case in the floodplains of large river systems where the mild topography has come about as a result of the deposition of river sediments over long periods. A case in point is a major feature of the Indus Plain in Pakistan. This plain is underlain by concealed ridges, one of which, a westward extension of the Aravalli Range in India, has virtually cut off the Punjab alluvial basin from the Indus basin. This is an important cause of the problem of waterlogging in the upper parts of the latter, i.e., there is no continuous groundwater basin extending from the Himalayan foothills to the vicinity of Multan, roughly half way to the sea (Kaul 1970).

Drainage and salinity

Problems of soil and irrigation water salinity are well known in many temperate countries as well as in the arid regions of the Mediterranean basin and many tropical and subtropical lands. However, as a result of direct and indirect influences of climate, the problem is much more widespread and acute in the arid and semi-arid zones. According to Yaron (1973) about one-third of the 200 million ha of irrigated land in the world is affected by salinity problems. Although every soil contains soluble salts in some degree, it is only when the accumulation of these reaches a level harmful to plant growth that a salinity condition is said to have developed. This means, in effect, that the plant defines the salinity of the soil according to its tolerance.

Mineralization of water resources, especially of groundwater, is a universal problem in arid regions. Possible causes are evaporation from open water surfaces and shallow groundwater; fossil brines from ancient lagoons and inland lakes; connate salts precipitated together in fine-grained marine sediments; airborne salts deposited by precipitation and in the form of dry fallout; and direct contamination by the sea, as for example in the case of brackish springs that issue from limestone formations (Elgabaly 1971; Mandel 1973).

Near the sea in many parts of the Mediterranean region and in aquifers near the United Arab Emirates coast, marked salinity is sometimes a widespread feature of

groundwater. Simpson (1968) records that some 50% of all desert lands in Australia are believed to be underlain by saline water.

The dominant chemical ions in natural waters are chloride, sulphate, bicarbonate, sodium, potassium, calcium, and magnesium. Their relative abundances distinguish the geochemical origins of water and the natural environments through which it has passed. Concentrations of salts in groundwater can be very high. Thus, Elgabaly (1971) speaks of ranges of 25–100 g/L. Curry et al. (in Unesco 1974) state that, in irrigation areas in the headwaters of the Murray River in Eastern Australia, the natural groundwater has a salinity almost equal to that of seawater. Firmin (1968), describing efforts to grow trees with saline water in Kuwait where natural sweet water is extremely scarce, speaks of concentrations as high as 4000–5000 ppm. He also discusses the relevance to plant growth in the area of varying ratios of different ions and of the presence or absence of trace elements, e.g., boron and zinc. Khatib (1971), in his review of existing and potential salinity-affected soils in the Middle East, noted that the pattern of occurrence of different salts changes along the courses of major rivers. Carbonates tend to be most strongly represented in the upper reaches, sulphates are prominent in the floodplains of the central regions, and chlorides (the most soluble) predominate in the lower reaches and delta regions. This pattern also characterizes the distribution of these ions in the Indus basin in Pakistan.

In a useful review of salt-affected soils in Pakistan, Shah Mohammad (1978) explained that, from a plant-growth point of view, the condition takes one of three forms. *Sodic soils* — a less ambiguous term than "alkaline" — have a high exchangeable sodium (often sodium carbonate) content, low electrical conductivity of the saturation extract, and very high pHs, i.e., in the range 8.5–10. *Saline soils* contain an excess of soluble salts, particularly neutral chlorides, and they have higher electrical conductivity than the former type, and pH is usually less than 8.5. *Saline–sodic soils* have excesses of both soluble salts and exchangeable sodium and the pH may or may not exceed 8.5. Although all three conditions affect plant growth adversely, the sodic condition breaks down soil structure as well and renders the soil more or less impermeable to water. In this respect, by contrast, saline soils have reasonably good structure that readily permits leaching.

Vegetation

Except in restricted favourable localities, the vegetation of arid areas is sparse and usually highly specialized morphologically and physiologically. Xeromorphic foliage structure and function, biological controls over transportation and metabolism, the development of moisture and nutrient storage organs, spiny or otherwise harshly textured external features, and the ephemeral nature of many annuals are common and well documented. As conditions for plant growth become progressively more favourable with lessening aridity, specialization becomes a less pronounced feature (Gindel 1964, 1971, 1973; McGinnies 1968).

Because specialization of plant forms becomes a more marked characteristic with increasing aridity, it follows that the vegetation usually includes several valuable indicators of ecological conditions. Thus, in the Middle East and the Indus Plain, *Prosopis cineraria* and *Capparis aphylla*, when prevalent in the vegetation, indicate soils that are free from excessive salinity and suitable for irrigated plantations whereas *Salvadora persica* and *Salvadora oleoides*, among many others, indicate poor soils infested with salts and unfit for plantations without prior reclamation measures. *Tamarix articulata*, *Tamarix dioica*, and *Sueda* species also indicate poor calcareous soils.

It is interesting to note that toward the drier end of the spectrum of arid and semi-arid climates, few species provide food for the indigenous people although foliage and flowers of some of them can be useful supplements.

In spite of a certain robustness and tenacity of life that arid zone vegetation can display, it is widely recognized that, under low and erratic rainfall conditions, it is in a state of relatively delicate balance with the environment. It can withstand human influence, e.g., gathering fuelwood and small construction materials and grazing and browsing, to a moderate extent. However, as human demands and domestic herds and flocks increase, the impact is more marked: the extent of degradation and denudation of the vegetative and soil cover in these fragile environments increases rapidly. Regeneration and growth, particularly of the woody vegetation, is normally slow even in undisturbed areas. On the other hand, where soil occurs in adequate depth, without the undesirable features of salinity or alkalinity, irrigation at appropriate rates and with proper controls, allied with the favourable natural conditions of temperature and radiation, at once demonstrates the inherently high productivity of arid-zone soils.

Land Use and the Need for Irrigation

Increasing populations and urbanization are features of arid and semi-arid regions just as they are of others. Associated with these trends are increased demands for timber for fuel (the primary domestic energy source in many countries), building, and other purposes, and for fodder and browse for camels, goats, sheep, and cattle. Gathering these commodities from the natural woodland commonly destroys the original vegetation over an expanding radius round every town and village. At the same time, much of the land is used for agricultural production. The drier the area, the greater is the tendency for wind erosion and dune formation to follow in the wake of this degradation.

In arid and semi-arid landscapes, the areas available for reliable rainfed agricultural production are limited and usually insufficient to produce enough food and fodder to meet demands. Irrigation is accordingly practiced to raise production severalfold — if possible to the full capability of the soils — by removing the single limiting climatic factor of water deficiency (Yaron and Vink 1973). Although agricultural production rightly receives priority allocation of the available irrigable lands and water, the same means can be and often are used to enhance wood production. The effect of irrigation in increasing production is most marked in arid and semi-arid zones. The manner in which it is used varies as climates become less arid. In arid areas, it can raise production from very low levels of yield to very high ones; in savanna areas and Mediterranean climates, it can extend the growing season and raise the possibility for diversifying crops and their rotations; in steppe climates, it can transform the landscape into highly productive land. The scale then tips: in subhumid climates, the high capital and other costs of much large-scale irrigation, including irrigated forest plantation, are usually avoided by planting drought-resistant species and irrigation is generally restricted to high-value agricultural crops (Fuchs 1973a).

The use of irrigation presents important opportunities to produce wood, particularly in the drier areas of the world where this is the major form of domestic fuel and trees are required to meet needs for other commodities, including poles, fodder, and shelter. However, in these regions, water and irrigable land are also required for food production, which is usually a higher priority.

3. Irrigated Forest Plantation Experience

The potential for high levels of production through irrigation in arid and semi-arid areas has been noted by several foresters and forest scientists concerned with this field. They have pointed to such benefits arising from it as assurance of successful planting, high yields from fast-growing crops, the creation of productive plantations in unproductive desert lands, and the avoidance of risks due to climatic stresses and vagaries. However, many of those experienced in the field have warned of the serious physical and biological problems that can arise, sometimes with important economic, social, and political consequences. In extreme cases, irrigation itself has been one of the causes of desertification (Khatib 1971; Barbier 1978; Wood et al. 1982).

Because irrigated forestry is seldom practiced on its own, separate from irrigated agriculture, its general history and background should be considered in the same context. Some impression of the scale of irrigation is given by Shmueli (1973) who notes that, for various social, political, and economic reasons, less than half of the 500 million ha of land in the drier parts of the world that are potentially suitable for irrigation are actually used for that purpose. In 1800, some 10 million ha were so used; by 1900, the area had become 40 million ha; by 1950, 160 million ha; and, by 1969, 200 million ha. At a regional level, although some 24 million ha in the Mediterranean basin are potentially suitable for irrigation, the area actually used is barely 8 million ha, or 3% of the total area of the region exclusive of deserts (Glesinger 1960). At the national level, 12 million ha of land were under irrigation in Pakistan in 1979, involving some 78 000 small, individual, water-conveyance systems (Trout 1979). In 17 western states of the USA, 14 million ha were under irrigation in 1910 and, by 1960, this had risen to 30.7 million ha. Although this increase was accompanied and assisted by the provision of cheap water and technology based on research on plant–water–soil relations, specialists have observed that there was no marked general improvement in the efficiency of water application (Shmueli 1973). The important implications of this observation underlie a statement of a Unesco commission to the effect that water can be either a productive resource or a destructive hazard — which it becomes in practice depends on management of the soil, the crops grown, and, most important of all, the water that is applied (Unesco 1974).

The first well recorded civilization of the Tigris and Euphrates Plain at the southeastern end of the Fertile Crescent in Mesopotamia, which existed 6000–7000 years ago, learned to produce crops from the desert by irrigation. The Nahrwan Canal, fed from the Tigris and draining to the Euphrates, distributed seasonal mountain rainfall stored above the Beled Dam to grow crops on several hundred square kilometres of desert soils. The fertility of the area became legendary. For 3000 years, this harnessing of natural resources, backed by strong government, supported Babylon's population of up to 25 million people. Finally, however, weakening of the essential central authority and discipline, and the ensuing increases in salinity com-

bined with destruction of the vegetative cover in the headwaters areas, from where the ensuing floods eventually buried the canal in transported sediment, combined to destroy the system. Between 4000 and 2000 B.C., the land was ruined by salinity to the extent that it has still not recovered. This loss of productivity was associated with the application of excess irrigation water, seepage from canals, a rising water table, and evaporation causing salt deposits at the soil surface. Of present day Iraq's potentially irrigable land, 20–30% is still useless. Whereas wheat and barley had been grown at first in equal quantities and average yields had been some 2 t/ha, by 1700 B.C., no wheat was grown in southern Iraq, but only salt-tolerant barley. The immense social, demographic, and economic effects of this decline in irrigated agriculture led to the break-up of the Sumerian civilization. Expansion of successive civilizations followed, e.g., that based on the very large irrigation system developed by the Persians after the conquest of Mesopotamia by Alexander the Great in the 4th century A.D. These developments were also subsequently plagued by soil salinity although never as severely as the earlier examples. The Persian irrigation system fell into disrepair after the Islamic invasion in the 12th century and has not been restored. A leading world civilization perished. When the Mongols invaded the area in the 13th century, all they found in legendary Mesopotamia was devastation. Today, the area is largely desert, occupied by 10 million people who eke out some of the world's lowest crop yields (Unesco 1974; Eckholm 1975; Pillsbury 1981).

An added secondary threat to food production was the burden of silt that was carried into the irrigated areas by the canals. In 5000 years, a layer of silt up to 10 m deep was laid down in this way over parts of the Tigris–Euphrates basin. Widespread coordinated action became essential to the survival of the system and huge amounts of silt and fine sand are still to be seen in northern Iraq.

The largest and oldest of the world's irrigation systems on the vast river systems of the Tigris, Euphrates, Ganges, and Indus have been struggling with the problems of salinity, waterlogging, and sedimentation for centuries. Canal seepage slowly builds up groundwater levels, aided by the universal tendency of farmers and other irrigationists to overwater. Too often, drainage systems have not been constructed on a sufficient scale to remove surplus water. Leaching salts out of the soil by the application of excess quantities of water offers a solution only where drainage is adequate to carry it away and where disposal of the saline drainage water into a river system is acceptable to downstream users. When the saline groundwater rises sufficiently to invade the crop's rooting zone, the increased osmotic pressure due to the salts causes plants to wilt. The farmer assumes that the wilting indicates a need for more water, which is added if it is available, so that, in the end, the salts reach the surface and the area is abandoned.

A study of much of the foregoing history of irrigation by the Director-General of Antiquities in Iraq and the Oriental Institute of the University of Chicago (cited in Unesco 1974) emphasized three important lessons that are widely applicable to irrigation in arid and semi-arid zones.

- A very close relationship exists between successful irrigated agriculture and the existence of a stable central government, because, to be effective, control must extend beyond regional borders to the source of water supplies. It must also ensure proper arrangements for disposal of drainage water.
- Sedimentation, in addition to blocking canals and subsequently leading to the breaking of their banks, may insidiously cause long-term destruction of

irrigation schemes by raising the level of the land, leading to the loss of command by the water-supply system.

- Losses from salinity have been reported among the earliest written records of irrigation. Although control by leaching and drainage seems to have been understood, it has not been practiced with sufficient determination and, thus, deterioration has continued. Indeed, for example, it seemed probable that, in 1974, on the Indus and Ganges irrigation systems, a greater total area of productive irrigation land was abandoned each year because of salinity than was opened under new irrigation schemes.

These lessons and the highlights of the history of old irrigation systems briefly reviewed here emphasize the problems that can frustrate irrigation developments and the imperative need for realism in design and operation of such schemes. As will be seen later, there are indications that the lessons are still sometimes unheeded!

Regional and Country Accounts

The series of outline reviews that follows is not intended to be an exhaustive account of irrigated forestry in the regions or countries concerned but rather to highlight the salient features of the programs covered, some of the principles they embrace or illustrate, and experience that might guide practice in other areas. Comprehensive published accounts of individual projects or for specific countries are seldom available and in many cases the available reports are not up to date. However, the papers cited contain, for those who require it, more detail than can be included here and would serve as introductory reading where there is interest in inquiring more deeply into practices in any particular country.

South Asia and the Middle East

Pakistan

Irrigated plantation forestry on a large scale was practiced for the first time, anywhere, on the Indus Plains of what is now Pakistan. Planting began in 1864, primarily to provide fuel for the operation of the railways, along the routes of which the plantations were sited. By 1926, the area planted was 3550 ha, by 1960, almost 80 000 ha, and, in 1967, nearly 100 000 ha. The plantations were made up of a large number of blocks of various sizes, from a few hundred to several thousand hectares, distributed through the extensive irrigated agricultural area in the valleys of the Indus and its major tributaries in the plains area. In addition to fuelwood, these plantations have yielded substantial quantities of sawlogs, and wood for special purposes such as the manufacture of sporting goods, and have formed the basis for important local cottage industries, e.g., sericulture and apiculture. Hiley (1930) estimated that, by 1913–14, the whole of the capital cost of the Changa Manga block of plantations, the oldest, had been paid off by income from the plantations, the financial yield from which had been 4.67%.

The principles and practices underlying the development of these plantations were summarized by Troup (1921) and described in detail in two manuals by Ali (1960, 1962) and by Khan (1961). Ali's manuals give guidelines regarding site factors; plant–soil–water relations; criteria for site and species selection and silvicultural practice; and describe the elaborate, costly system of gravity irrigation channels leading ultimately into series of 30-cm deep trenches at 3-m intervals along which the trees were planted, usually at 2 m in-row spacing. These were used almost exclusively

until very recently when flood irrigation came into favour. Ali also gave guidelines concerning rates and methods of applying water, waterlogging, salinity, and other problems that might be encountered and the means to deal with them. Ali noted, as also did Khattack (1976), that layouts, irrigation techniques, and silvicultural practices were developed by trial and error over the years and that the foresters involved tended to be less than adequately informed about the principles of irrigation.

The principal species used have always been *Dalbergia sissoo*, *Acacia nilotica*, and *Morus alba*, with smaller amounts of *Albizia procera*, *Albizia lebbek*, *Bombax ceiba*, *Eucalyptus camaldulensis*, and various clones of *Populus* × *euramericana*. *Dalbergia sissoo* and *Populus* × *euramericana* often give the impression that they are maladjusted to the very long growing season and short winter rest period of the Indus Plain. The *Albizia* species do not all have the compact growth habit necessary for good plantation species. *Dalbergia sissoo* and *M. alba* have commonly been grown in mixture with the result that wood production is usually appreciably lower than that of either species grown in pure stands (Lerche and Khan 1967).

Production from the irrigated plantations has declined over the years due to several factors, including uneven establishment because inappropriate planting methods were used; less than optimal site leveling, which affects the evenness of water application; irregular or insufficient watering due sometimes to the location of plantations at the ends of water distribution systems but also, in the older plantations, to the levels of the plantations having been raised by accumulating silt; inadequate canal maintenance; and poor scheduling and monitoring of irrigation. In addition, water is often not available in the formally allocated quantities upon which the design was based. Yields have also been depressed by excessive weed growth (particularly grass, *Prosopis glandulosa*, and *Prosopis juliflora*) and by silvicultural management regimes that include heavy thinnings at about the 6th year after planting so that the site is inadequately occupied by the crop for the remainder of the rotation. Management of the plantations under the coppice-with-standards or other two-storey systems has led to the lower storey being suppressed by the excessively spreading crowns of the trees in the upper one. These defects have been exacerbated by the tendency for the trees, planted along 30-cm deep trenches at 3-m intervals, to develop root systems that are strongly oriented along these channels. As a result they lean over or are windthrown as they mature, particularly where they have suffered root disease (Lerche and Khan 1967; M.I. Sheikh, Pakistan Forest Institute, Peshawar, Pakistan, personal communication, 1985). Regeneration of the *D. sissoo* stands is usually by replanting but favourable results can also be obtained by using the coppice root-sucker regrowth that follows clear cutting (Khan 1960a).

Some impressive results have followed recent efforts to improve production, under intensive monitoring, by using flood irrigation instead of trenches, setting high performance standards in respect of site preparation (particularly leveling) and regularity of watering, and by adopting spacing and thinning schedules that reduce weed growth in the early years and optimize volume production. However, maintaining level flood basins throughout the long rotations over which tree crops are grown is difficult and correcting deficiencies in levels that develop after the crops are established is virtually impossible.

For many years, government plantation establishment was effected by allowing farmers to grow agricultural crops between the rows of young trees during the first 2 or 3 years. This system has fallen into disfavour because it proved difficult to operate and administer and because it was commonly conducted in a manner that favoured the

farmer's crops at the expense of the trees (Khattack 1976). On the other hand, the planting of individual trees, lines of trees, and block plantations (*houris*) of soil-improving leguminous species, or fruit-producing as well as wood-yielding species, by farmers on their own land, and integrating them with agricultural cropping, is highly successful and productive over large areas, e.g., the irrigated farming areas of Punjab.

Poplars are grown very successfully along irrigated field boundaries by farmers in the Northwest Frontier Province and Punjab. There is great potential for extending the integration of tree growing with agricultural cropping in Pakistan (Sheikh 1978, 1980, 1981, 1982; Sheikh and Raza-ul-Haq 1982a, b).

In common with the irrigated agricultural lands within which they are located, the plantations in the Indus Plain suffer widely from waterlogging and various degrees of infestation with salts. Estimates of the extent to which the irrigated lands are affected vary. In 1952–54, it was estimated that 20% of 11.4 million ha surveyed in Punjab was salt-affected, as was 56% of the 7.25 million ha surveyed in Sind and 5% of the 0.55 million ha covered in Northwest Frontier Province. Of the area surveyed in Punjab, 16% was waterlogged, as was 38% of that in Sind. It was estimated in 1976 that, of the 4.5 million ha of salt-affected lands, 87% was affected in this way by fossil, i.e., natural, salinity that had developed over very long periods. The remaining 15% were affected by secondary, man-induced salinity (Shah Mohammad 1978). Whereas 16 000–20 000 ha were being added annually to the area affected by waterlogging and salinity in 1945–46, the rate had increased to 45 000 ha/year in 1962–63, two-thirds of it in the lower parts of the Indus Plain (Khatib 1971).

The man-made share of these salinity problems arises principally from raising of the water table through the continuous, region-wide passage of massive quantities of water in unlined canals, excessive applications of water by farmers, and inadequate natural and artificial drainage. To be effective, reclamation and amelioration must be undertaken on a very large scale. This is, in fact, being done through an agency specially set up for the purpose that began operations in 1960. The plan involves the construction of thousands of kilometres of drains to take surplus water away, massive use of tube wells to lower the water table, followed by a series of soil amelioration practices that include leaching with sweet water. In the 1st year, 1964, the water table had dropped an average of about 28 cm in the areas treated and hopes for success were rising by 1970. Progress is slowed by the extensive financing that is required but, in general, the country believes it is holding its own: broadly speaking, new losses of productivity to salinity and waterlogging are being balanced by gains due to reclamation (Eckholm 1975). Foresters are participating in these measures by applying design and operational practices that are currently regarded as sound in all new plantation developments and by upgrading existing, unsound systems. Ultimate reclamation of the affected areas will take a long time.

The water needs and responses of the species being grown are imperfectly known. Laboratory-scale tests of water consumption by seedlings have indicated real differences in growth in relation to water use by *Acacia arabica*, *Eucalyptus tereticornis*, *E. camaldulensis*, *M. alba*, *D. sissoo*, and *Tamarix articulata* (Raeder-Riotzsch and Masrur 1968). The next step, of deriving scientifically based watering regimes that relate to soil and climatic conditions in the field, has been in progress for several years. It has been found that optimum growth of *D. sissoo* results from applications totaling 0.9–1.35 m/year and that *E. camaldulensis*, *M. alba*, and poplars require less than 1.5 m of water per year in the range of conditions tested for optimum growth (Sheikh 1974a and personal communication, 1985).

India

From the early 1950s, steps were taken to develop irrigated plantations in northwestern India. The species, layouts, and methods used were those that had become traditional in the Indus Plains in adjacent parts of Pakistan (Singh 1960; Singh 1963). These developments have not been on anything like the scale of the plantations in the Indus Valley. However, they have been beset by problems of unreliability of water supplies, soil salinity, and the like, similar to those that occur in Pakistan. Successful irrigated plantation development has also been handicapped by the lack of developed irrigation regimes. Investigations have been made to ensure that water quality is suitable for irrigation of tree plantations and for supplementing rainfall to leach salts beyond the rooting zones of trees. The speed with which water tables can be raised by irrigation developments and the extent of such events were illustrated in the Bhakra Canal area of 2.7 million ha in Punjab, where well data go back to 1895 and a large irrigation scheme began in 1954. By 1963, the water table had risen 7–9 m and waterlogging and salinization of the irrigated soils had begun (Barghava 1948; Kanshik 1961; Singh 1963; Sharma 1973; Singh and Singh in Unesco 1974; Bhatia 1980; Tomar and Yadav 1980).

The most impressive development of irrigated forestry, virtually anywhere, in recent years has occurred in the irrigated farming areas of India, e.g., in Gujarat (where these new initiatives started), Haryana, Uttar Pradesh, Bihar, West Bengal, and in the southern states of the country. These developments, which have been supported largely through funding by the World Bank, are documented in the working papers of that institution and have not been reported comprehensively in the forestry or other scientific literature. From personal observation and communications from officials of the Indian Forest Service and the World Bank, it is clear that Indian farmers are highly skilled in integrating the planting and tending of trees with their other farming operations, and fully aware and appreciative of the economic benefits that result. In a few years, the landscapes of the farming areas concerned have begun to be transformed by the widespread growth of trees in the formerly virtually treeless agricultural areas. According to Shiva et al. (1982) some 10 000 farmers in one district of Gujarat have turned to *Eucalyptus* farming on irrigated land because it is more profitable than growing wheat or sugarcane. The state forest authorities, in particular, have been restructured profoundly in adapting to these new initiatives and needs, including the necessity for extension services.

A range of species providing fuelwood, poles, fruit, fodder, and shade is used, prominent among them *E. camaldulensis*, *Eucalyptus* "hybrid" (= *E. tereticornis*),[1] *A. nilotica*, *Azadirachta indica*, *Albizia* species, mango, and very fast growing, short-rotation species such as *Sesbania grandiflora*. Seedlings are usually distributed free or at low cost from state nurseries but many farmers raise their own stock.

A lysimeter study of water consumption in relation to biomass production in seedlings during their 1st year was undertaken in relation to several species used under irrigation in Uttar Pradesh: *Pongamia pinnata*, *A. lebbeck*, *Acacia auriculiformis*, *D. sissoo*, *Syzigium cuminii*, and *Eucalyptus* "hybrid." A strong, positive correlation was found between water consumption and biomass production (growth). The species tested are listed here in order from the slowest to the fastest growers, and from the lowest to the highest in terms of water consumption per unit of biomass produced.

[1] *Eucalyptus* "hybrid" has been identified as *E. tereticornis* (FAO 1979a). The Indian practice of referring to it as "hybrid" is followed here.

Eucalyptus "hybrid," the fastest grower, used 0.51 L of water to produce each gram of biomass whereas *P. pinnata*, the slowest grower, used 1.30 L (Chaturvedi et al. 1984).

Financial analysis has indicated very favourable results for a 65-ha farm near Ahmedabad in Gujarat, on which the owner converted wholly to growing *Eucalyptus* poles under irrigation. With internal rates of return of 129% for the initial crop and 213% for subsequent coppice crops (before taking land values into account), the tree crops were appreciably more lucrative than annual agricultural crops (Gupta 1979).

Iraq

The early history of irrigation in the Tigris–Euphrates area, of which Iraq is a part, is discussed in the introductory section of this chapter. Of all irrigable land in this country, 70–80% is now more or less saline. Areas cultivated for the first time in 600 years have yielded only 5–10 agricultural crops before they have become too salty to cultivate again (Glesinger 1960).

Pryor (1953), reporting on irrigated trials of *E. camaldulensis* and *Eucalyptus microtheca*, noted that results were very promising in areas where drainage is adequate and salinity not a limiting factor. Patches of *E. camaldulensis* in some areas were chlorotic. He suggested that 10% of state land suitable for the purpose, including marginal agricultural land, should be reserved for the production of much-needed wood by irrigation and that many additional *Eucalyptus* species native to areas in Australia with climates similar to that of Iraq should be tested. He found it difficult to ascertain what irrigation regimes were in use but suggested that some reduction of water applied might be advantageous, as might experimentation on the best timing, frequency, and rates of application.

Very promising trials of *E. camaldulensis*, *E. tereticornis*, *Casuarina equisetifolia*, *Platanus orientalis*, *D. sissoo*, *Melia azaderach*, and *T. articulata* were started in 1948 near the junction of the Tigris and Lower Zab rivers. No records are available of the irrigation rates used but it is probable that the trees were overwatered. Irrigated species and cultural trials were continued until the beginning of the present decade with financial support from the United Nations Development Programme (UNDP) and FAO. *Eucalyptus camaldulensis* grew in the Omari plantations in the Tigris Valley at rates representing as much as 37 m^3 of wood per hectare per year at 5 years of age (Gorrie 1956; Barbier 1978). In view of the country's demands for wood and on the basis of some economic analyses of data from the trials, Busby (1979) recommended that a program to plant 34 000 ha of plantations be undertaken on the Mesopotamian Plain.

Unfortunately, informal reports from officials of UNDP and FAO indicate that the plantations have been neglected for 2–3 years as a result of the Iraq–Iran war and, in the absence of watering, there have been wholesale deaths of trees.

Kuwait

The climate of Kuwait is harsh. Some of the salient features are hot, dry summers during which sandstorms occur, alternating with mild to cold winters (the minimum recorded temperature is −4°C); relative humidities vary from a maximum of 80% in December to 13% in June; and a mean annual rainfall of about 100 mm at the coast and lower inland, compared with an annual total potential evaporation of 5000 mm. The soils are infertile, having poorly developed profiles, frequently high salinity, and a calcium carbonate pan at 0.7–1.7 m depth. Water available for tree or agricultural irrigation includes brackish desalinated water, untreated sewage water, treated sewage

effluent, or highly saline, highly limey water with a pH of 8–9 in shallow aquifers. The salinity of the seawater is relatively low as a result of the limitations of currents in the Gulf. This water is thus favourable for the growth of mangroves along the coast.

In these unlikely conditions, the forestry department has carried out irrigated trials with *P. juliflora*, *Zizyphus spina-christi*, and *E. calmaldulensis*, which they found to be tolerant of salinities almost approaching that of seawater, provided that there is permanent moisture in the root zone and that magnesium–calcium ratios are not toxic. A large number of other salt-tolerant tree species and shrubs were tested in saline soils using water with 4400 ppm of salts. As a result of the tests, they were listed in descending order as to their tolerance of salinity expressed as electrical conductivity of the growing medium (see appendix 2). The investigators observed and listed trees growing near saline wells, including species that appeared to tolerate high sodium–calcium ratios and high ratios of sodium to calcium plus magnesium. A number of treatments to lessen the effects of salinity were also tested, e.g., profile aeration, additions of sulphur to reduce the pH, plastic aprons round the stems to reduce evaporation from the soil, ridging, deep planting, and irrigation at short intervals or continuously at night (by sprinkling). Evaporation from the soil surface was found to be a most important factor to control (Firmin 1968).

Two schemes were initiated in 1962 to develop shelterbelts along the Kuwait–Jahara road and for shelterbelts to protect the township and surrounding area of Jahara (Firmin 1968). The standard technique was to dig 1-m deep trenches, apply treated sewage water brought from Kuwait by tanker, refill the trenches with soil, and plant long (1 m) cuttings of *Tamarix aphylla*, the most suitable species for the purpose. Over 200 species or provenances were screened in elimination trials at six sites. Also tested were type of plant material to use, reduced watering, salt tolerance, fertilizers, and mechanized site preparation. The most promising species were *T. aphylla*, *E. camaldulensis* var. *obtusa*, *Eucalyptus coolabah* (= *E. microtheca*), and *Acacia salicina*. Correct choice of provenance was demonstrated to be important in several instances. Extension of the trials and larger scale plantations were recommended if suitable land, water, and funds were available. Although the results of later work or applications of the results of these important trials have apparently not been published, consultants were used by the Kuwait Ministry of Public Works to design agricultural and forestry developments using treated sewage effluent. Some 3000 ha of plantations have already been established by the government around Kuwait City. A 7000-ha program was designed for the use of much of the sewage effluent that would become available in 1980–2000 for high intensity forestry production, environmental protection, windbreaks for crop protection, and unirrigated or minimal irrigation forestry (Wood and Synott 1978).

United Arab Emirates

The earliest plantations in Abu Dhabi, near Al Ain, which is some 170 km inland from the port of Abu Dhabi, were planted in 1968 as roadside strips using a drip irrigation system. Several species were used, including *E. camaldulensis*, *E. microtheca*, *C. equisetifolia*, *Parkinsonia aculeata*, and *P. juliflora*, some of which reached heights of 5 m in 5 years (Satchell 1978). About 6000 m^3 of water with a salt concentration of 2–15 g/L were applied per hectare per year (Barbier 1978).

In 1972, a start was made with establishing 430 ha of plantations in two areas well away from main roads, southwest of Al Ain, for their amenity value, perhaps later to be wildlife parks or recreation areas (Wood et al. 1975). The general altitude is 300 m and

the annual rainfall less than 100 mm. Relative humidity is lower than that at the coast and particularly dry winds blow from the Empty Quarter of Arabia. The planting areas are partly on flat, silty or gravelly plains and partly on shifting sand dunes. Soil depth, fertility, and texture vary greatly and indurated gravel horizons, often containing an abundance of gypsum, occur. Water for irrigation is from boreholes and displays considerable variation in salinity, i.e., from 2500 to 7000 ppm. When waters of high salinity are used for irrigation, it is desirable either to use relatively large quantities to minimize the buildup of salinity in the root zone or to reduce surface evaporation to a minimum and to ensure maximum utilization of water by the plants. For these reasons and to conserve scarce water, a trickle irrigation system was selected and the plantations were divided up for management into 20–25 ha blocks, each the charge of one person. Four indigenous species were selected: *Acacia tortilis*, *A. nilotica*, *Prosopis cineraria*, and *Z. spina-christi*. Local seed provenances were used. Although April–October are the hottest months, planting was done in August when daytime temperatures drop noticeably. Palm fronds or netting were used to protect the 30-cm transplants from the abrasive effect of blown sand. Field survival of 80% was usual and the best plants were over 1.5 m tall after 1 year. Watering was at the minimum rate required for survival and steady growth. Insecticides were applied by spraying to protect the young plants from leaf miners, leaf hoppers, caterpillars, and spider mites and, through the irrigation system, to control termites and cockchafer grubs. The authors expect that only two of the species can survive without irrigation: *P. cineraria*, because it is capable of producing a deep tap root, and *A. tortilis*, which, although it is very shallow rooting, is capable of obtaining its water from occasional rainfall and dew.

Satchell (1978) recorded that landscape contractors had recently undertaken the afforestation of a further 200 ha in Abu Dhabi and of other areas in Dubai and Sharjah. Plantations totaling 960 ha were also planned for the oil centres of Tarif and Jebel in Abu Dhabi.

Other Middle Eastern countries

According to Khatib (1971) irrigation areas are commonly affected by waterlogging and salinity in South Yemen, the Yemen Arab Republic, Somalia, Saudi Arabia, and Iran. In Iran, 5% of the irrigated arable area was waterlogged by 1971 and Eckholm (1975) noted that somewhat saline water was being used for irrigation of large areas of land.

The Mediterranean region

The literature on irrigation application and research in the Mediterranean region strongly emphasizes concern about limited water quantities (a high proportion of it comes from wells), its frequently saline nature, the limited extent of irrigable land, the frequency with which this tends to be (or readily becomes) saline, and the consequent need for well conceived and carefully tested methods and schedules and soil-drainage arrangements. Not surprisingly, irrigated forest plantations are nowhere extensive in the region and their economics are carefully monitored and compared with agricultural crop alternatives. The experience reviewed here suggests that mankind's ingenuity reaches commendable heights when it is challenged by conditions of water scarcity and soil that at first suggest that successful tree culture will be unlikely. On the other hand, its lapses and omissions often seem to be most serious and unexpected when the soil is potentially excellent and the water abundant and sweet!

Tunisia

Dates, olives, and annual crops have been produced for centuries under irrigation with water that is brackish due to natural underground salt deposits. The area under irrigation, primarily of agricultural crops, has increased markedly in recent years as have efforts to select salt-tolerant plant materials and to avoid accumulation of salts in the soil. Many studies have been undertaken in several representative locations across the country in relation to these concerns by an active agricultural research service. One of these, for example, took place in a 200-mm rainfall area near Sfax where artesian well water containing up to 11 g of salts per litre was used. Applying this water at a rate of 6.9 mm/day, i.e., in excess of the potential evapotranspiration rate of 5.5 mm/day, resulted in a rise of 3 m in the water table in 4 years. As a result, root systems of crops were reduced, yields declined, and barren, dusty patches occurred on the soil surface. The situation was corrected quite readily by installing tile drainage, reducing irrigation amounts, increasing the frequency of applications, and leaching out the salts in winter. The depth to which the water table is reduced in any specific area has been found to be critical: over wide areas in the centre and south of the country, including those oases and depressions where date palms, *Eucalyptus occidentalis*, and *E. camaldulensis* are grown, water tables 1.4–1.7 m below the surface — and not closer — are satisfactory. The optimum irrigation–leaching–drainage arrangements and regime are worked out to suit each situation (Cointepas 1968; Van Hoorn et al. 1968; Arar 1975).

Algeria

Irrigation trials of fruit trees, palms, and several timber species, including *E. occidentalis* and *C. equisetifolia*, have given very promising results in arid conditions in the Igli–Adrar area near the border between Algeria and Morocco. The trials indicate the importance of careful leveling and other features of site preparation, scheduling of irrigation, and drainage to offset the tendency for salinity to build up (Durand 1958). Metro (in Kaul 1970) described successful growth under irrigation of small amenity plantations and shelterbelts in a desert area at the base of Irara. *Eucalyptus gomphocephala*, *E. camaldulensis*, and *E. occidentalis* were the most successful species but several others also grew satisfactorily. Irrigation was done with somewhat saline water, heavy dosages being applied "so that the water would penetrate to 1–2 m." Underground drainage was provided where the water table built up to less than 2 m below the surface. Watering was stopped at the end of summer to encourage deep rooting. Copious quantities of water were used to leach out salts when these were shown by tree symptoms to be building up. It would be of interest to know whether these plantings, undertaken by an oil exploration company, continued to grow successfully because Metro (in Kaul 1970) gives the impression that rates of irrigation may possibly have been excessive.

Italy

In the drier Mediterranean climate areas of Italy and in Sicily, irrigation is widely used for annual fruit, vegetable, and other agricultural crops. Difficulties are encountered as a result of increasing salinity of the underground waters used from spring to late summer and of the buildup of soil salinity. Experiments have led to the adoption of irrigation regimes involving watering at short intervals and applications of mineral fertilizers and manure, with careful monitoring (presumably so that leaching can be done when soil salinity builds up) (Ficco 1968). Eccher and Lubyano (1969) recorded useful increases in volume production of *Pinus radiata* near Rome when it was

irrigated, even during a summer that was not unduly dry. More marked responses were forecast for similar treatments in southern Italy and Sicily where summers are much drier and more prolonged. Irrigation enhanced survival and growth of *Pinus maritima*, drip irrigation being efficient for the purpose (Grossi 1974, 1976).

Egypt

Specific records of tree growing under irrigation in ancient centres of civilization are rare. However, Rostovtzeff (in Hughes and Thirgood 1982), when sifting the evidence on the Ptolemaic period (3rd and 4th centuries B.C.) found records of a nationwide tree-planting project, which included planting along the banks of rivers and canals, to meet acute needs for wood in Egypt. The practice of canal-side windbreak and shelterbelt plantings persists to this day, their overall wood yields currently being of the order of 10 million m^3/year.

As in most Mediterranean countries, most irrigated tree plantation is integrated, in the form of lines, shelterbelts, and small groups of trees, with agriculture. Whether the trees thrive or not depends upon the conditions that are primarily created for agricultural cropping, or arise as a result of it. The highly productive Nile Valley retained its fertility through flushing by annual floods for thousands of years (Pillsbury 1981). This pattern has been interrupted by the construction of the Aswan Dam with the result that salinity and waterlogging have become serious problems in 30% of the arable area, particularly in the northern parts of the Delta where the soils are heaviest and have poor internal drainage (Khatib 1971; Eckholm 1975). After startlingly high crop yields during the first 4–5 years after extension of irrigation into the desert to the west of the Nile Delta, waterlogging, mainly due to canal seepage, and salinity have caused major deterioration of production here also (Hassan et al. 1970; UNO 1978).

Turkey

A now familiar trend marked an irrigation development on the Menemen Plain where no drainage arrangements were included in the system constructed in 1949. Large areas began to go out of production within 10 years as a result of waterlogging and salinity. More enlightened practices were introduced into irrigated poplar plantation areas at Izmit, however. Here, the quantities of irrigation water applied were not monitored during the first few years until sluices were introduced to regulate and measure discharge at key points after 1965. This was seen to be an important step to take because the water table was relatively shallow. It was also decided to test flood irrigation, as an alternative to the trench method initially installed, to encourage the development of better balanced, spreading root systems (Glesinger 1960; Chardenon 1969).

Israel

Irrigated forestry is practiced on a small scale in Israel with the tree crops usually being integrated with agriculture. As in agriculture, research and practice are conducted strictly along scientific lines. Thus, a replicated experiment was conducted over 4 years to determine the relative suitability of two representative poplar clones to be grown under sprinkler irrigation in the coastal plain, and to ascertain and test the most appropriate watering regime. The quantity and frequency of water to be applied to bring soil moisture to field capacity were determined and related to available soil moisture and rainfall (both of which would be monitored). Greater or lesser water applications resulted in suboptimal growth and reduced irrigation efficiency. It was found that water uptake was uniform at depths down to 120 cm, indicating very uniform root distribution in depth (Rawitz et al. 1966).

A similar approach was used in ascertaining the most favourable summer sprinkler irrigation regime for *E. camaldulensis*, which normally shows summer dormancy in Israel (Karschon 1970). The regime of watering that was determined increased growth by 100–120% by the 5th year compared with the rainfed control. Karschon cautioned that even this growth rate (which had not yet culminated) might not pay for the water required and that a firm judgment on this could only be made at the rotation age of about 12 years. It is not known whether any such later analysis was done.

Some 200 ornamentals, mainly trees, shrubs, and plants of potential amenity and economic value, were tested as to their suitability in the conditions of extreme aridity at Eilat on the coast. Average annual rainfall there is 20 mm, total salt content of the irrigation water is 2000–6000 mg/L but sometimes may be as high as 10 000 mg/L, and the water supply is sometimes limited. The soil is very light with a gypsum layer at 10–20 cm, which, being hygroscopic, might explain the survival of the plants when the water supply was sometimes interrupted. The light soil was noted to be an asset because it facilitated irrigation being conducted in such a way as to reduce the accumulation of salts. After 15 years, 29 tree species were listed (see appendix 3) that, in the local conditions, had done "excellently" and 17 that had done "well" (Boyko and Boyko 1968).

East, West, and Southern Africa

Sudan

The oldest irrigated plantation scheme in the Sudan had its beginnings with the initiation of species trials in 1932 in the Gezira cotton and sorghum irrigation project established in the 1920s on the west bank of the Blue Nile some 170 km upstream of its confluence with the White Nile. The decision to develop plantations at Gezira to provide fuel and poles for the inhabitants of the area was made in 1937 and planting began the same year at Fewar. The area experiences a severe summer drought and erratic rainfall that averages about 200 mm. The soils include extensive areas of black, alkaline, cracking clays, with a pH sometimes over 8.5. They originally carried sparse open grassland in the north, *Acacia mellifera* scrub in the centre, and *Acacia seyal–Balanites aegyptiaca* open woodland in the south. Use of water is governed by the Nile Waters Agreement with Egypt, which permits very little irrigation (virtually none for the plantations) from mid-March to mid-July. Tree planting was opposed at first for fear that it would encourage insects that damage cotton and birds that feed on the sorghum. The land allocated for plantations comprised unused pockets within the agricultural area. Particularly after 1951, these tended to be areas of irregular micro-relief used as dumping grounds for used and excess irrigation water, often of high salt content (Masson and Osman 1963; Bossard 1966b; Khan 1966d; Foggie 1967; Bayoumi 1972, 1976, 1977; Saleem 1973, 1975; Laurie 1974; Jackson 1976; Ahmed 1977; Ali 1979).

Eucalyptus microtheca (= *E. coolabah*) was chosen as the principal species to be planted. It is tolerant of great heat, the heavy montmorillonite soils of the area, and a degree of interruption of watering regimes. Unfortunately, all the seed used for the 1932 trials and for many years afterwards was derived from a single tree planted by Massey at Shambat in 1922 using seed from South Africa. This resulted in marked inbreeding depression that manifested itself in the very poor stem form that is a marked feature of virtually all local stands of this species. The bamboo *Oxytenanthera abyssinica* is also well suited to the irrigated plantation conditions.

Site preparation involved plowing to produce a series of low ridges 2.4–2.7 m apart, the depressions between which are used as irrigation channels. Foggie (1967) noted that leveling before ridging would be desirable as it would lead to more uniform watering. Seedlings 5–6 months old raised in polythene pots were planted at intervals of 2.4 m just above the irrigation level. Current practice is to space irrigation channels 3 m apart and to plant at 2-m intervals along them. Watering regimes were studied and proposed in detail by Ahmed (1969) and Khan (1966a), since when water has been applied nominally twice monthly from mid-July to mid-December and then monthly to mid-March. In practice, the quantities and frequencies applied have been very irregular — varying from overirrigation due to overwatering of adjacent agricultural lands, to underwatering due to a variety of factors including unevenness of site levels — and have led to dieback (Foggie 1967; Laurie 1974; Ali 1979). By 1971, such soil salinity problems as had occurred were localized and not unduly severe (Khatib 1971). The fact that irrigation areas in the Sudan are remarkably free of salinity problems is attributed to the fact that the montmorillonite clays that underlie most of them prevent percolation of irrigation water down to the water table or movement of salt-laden moisture by capillarity up from such depths.

By 1967, 3700 ha of plantations had been established in 63 separate areas. As a result of the variable cultural and other factors already mentioned, the growth and wood increment of the plantations have varied widely. For quality class III sites, which appear to make up most of the area, yields to rotation age of 8 years for seedling stands have varied from 1 (sometimes even less) to about 10 m^3/ha per year with a mean of about 6.5. In a few instances, on better sites, they have reached 23 m^3/ha. Foggie (1967) believed that 12 m^3/ha could be attained regularly with good site preparation and adequate and regular watering. In that event, he stated, the plantations would give better financial yields than the less productive agricultural areas. Ali (1979) pointed out that, contrary to the usual pattern, coppice yields were lower than those from seedling stands. He suggested investigating the biological or silvicultural cause. Ali's report gives the impression that this situation is due at least in part to poor felling methods, lack of careful attention to watering when it is needed by young coppice, and "drowning" of some stumps by overwatering. These factors weaken the stools, retard coppice regrowth, and cause the premature death of an unduly large proportion of stools.

Ali (1979) undertook a useful economic evaluation and appraisal of the plantation project. In particular, he studied three managerial aspects that led him to confirm the optimum seedling rotation as 8–9 years, and to query coppicing as a desirable alternative to replanting (in view of the falloff in yields already referred to). He made trenchant comments on choice of species, spacing, use of fertilizers, watering regimes, desirability of integrating tree growing, e.g., in shelterbelts, with agricultural production, and gave yield predictions for seedling and coppice stands of three site qualities.

Foggie's (1967) analysis examined the project both as to its silvicultural, irrigation, and forest management features, and, more importantly, in relation to current and projected needs for fuelwood and poles in the area. He recommended far-reaching improvements in the development and management of the plantations and a large expansion of irrigated plantations in the region to meet needs the magnitude of which seemed in prospect to be overwhelming. He also, like Saleem (1973, 1975), Bayoumi (1976, 1977), and Ali (1979), recommended large-scale integration with agriculture through the beneficial planting of shelterbelts, trials of which were described by Khan (1966d).

The second substantial and important irrigated plantation scheme to be undertaken in the country was the Khartoum Greenbelt where *E. microtheca* (the same inbred stock as that used at Gezira), *E. camaldulensis*, *E. tereticornis*, *A. mellifera*, and *Conocarpus lancifolius*, in particular, grow successfully under irrigation in an otherwise arid area. The project was initiated to make use of sewage effluent from the city of Khartoum. Its scope was extended by the provision later of canal water from the Gezira irrigation system. Site preparation, planting stock, planting method, rotations, and irrigation methods are similar to those described for Gezira, although the latter, due to the twin sources of water and to lining of canals, were much more regular and uniform and were not subject to the same annual interruption of water supply. Unfortunately, the water supply from the Gezira irrigation system failed for several months in 1984 and the plantations dependent on it died.

A considerable range of silvicultural development studies covering such aspects as species trials, nursery work, root studies, site preparation, planting, and irrigation schedules was undertaken in the 1960s (Bosshard 1966a, c; Bosshard and Wunder 1966; FAO 1969).

Irrigated plantations, nearly all of *E. microtheca*, are under development in several other agricultural irrigation scheme areas on soils similar to those at Gezira and using water from the Blue Nile or its tributaries. Thus 1000 ha of a planned 2100 ha have been planted at New Halfa on the Atbara River, 360 ha out of 2500 ha at Er Rahad on the Rahad River, and 450 ha at Khashm el Girba. Planting has also begun at the Suki, Kenaf, Sennar Sugar, Guneid Sugar, and Kenana Sugar schemes. The five sugar companies involved in some of these schemes plan to establish cane plantations totaling 63 000 ha. They all intend to use wastewater from their factories, treated if necessary to remove impurities, and waste irrigation water to grow *Eucalyptus* plantations for the production of fuel and poles. The company at Rahad has already installed wastewater treatment facilities. If all these plans reach fruition, and particularly if the necessary land becomes available, the extent of plantations could equal or exceed that of the cane fields. The capital costs of these developments would be moderated by the preexistence of much of the necessary infrastructure and the equipment for canal construction.

Traditionally, opportunity has been taken by the forest authorities to extend and intensify the regeneration and growth of *A. nilotica* stands in depressions along the Nile that are periodically flooded when the river is in spate. This rarely happens now as a result of the storage of much of the floodwater behind the several large dams that have been built on the Blue Nile and its tributaries. Resort is had, however, to continuation of this relatively small-scale, yet locally important, activity by pumping water, either from the river or from shallow wells beside it. Species other than *A. nilotica*, e.g., *Eucalyptus* species, are frequently used.

In the Nile Province in northern Sudan, there are several productive irrigated agricultural areas flanking the river. These areas and the irrigation canals in them are plagued by encroachment of blown sand from the adjacent desert. Protective irrigated shelterbelts are being established. They are clearly effective in preventing siltation where they have developed adequately as barriers in the path of the winds. They also enhance crop yields and are becoming important sources of fuelwood. Wood (1977) noted that these programs, which are being expanded, were hampered by a lack of adequate, comprehensive, detailed planning and financial analysis; doubts as to whether *E. microtheca*, *E. camaldulensis*, and *E. tereticornis*, or the provenances of these in use, are adequately suited to the light soils in the North; whether the 3 × 2 m

spacing is wide enough; and whether the system of irrigation (the same as that used at Gezira and the Khartoum Greenbelt) should not be reviewed because of the very large quantities of water used, and possibly replaced by some system of trickle or localized irrigation.

Sudan has opportunities to enhance agricultural crop production appreciably and to produce important quantities of wood through the development of appropriately designed networks of shelterbelts and canal-side plantations in the irrigated agricultural areas. Monitoring of the reduction of wind velocities in this way at Gezira (Salih 1967) indicated that the beneficial influence and reduction of evaporation should be as great as they are in other parts of the world. Bayoumi (1976, 1977) proposed a network of three-row irrigated shelterbelts for the Gezira that would cover the equivalent of 8400 ha or 1.5% of the scheme area. Properly established and managed, these belts could be expected to yield 84 000 m^3 of wood per year. Savings of water through reduced evaporation would amount to some 400 000 m^3/year, sufficient to irrigate the trees and an additional 33 600 ha of cotton. Overall crop yields from the areas protected would be increased by 20% or more. Five-row belts would take up about 2.5% of the scheme area; wood yields would be almost double the above value of 84 000 m^3; and crop and environmental benefits probably would also be greater. It is probable that such drawbacks as interference with aerial crop spraying and the harbouring of noxious birds could be minimized through shelterbelt design (including choice of species) and genetic manipulation of the crops affected by the birds.

During the last 3 or 4 years, pilot-scale initiatives have been undertaken by organizations such as the Sudan Renewable Energy Program to encourage small and large farmers and farming corporations to grow shelterbelts in conjunction with crops and livestock production and to establish irrigated block plantations on appropriate areas of waste land.

Foggie's (1967) analysis and forecasts of fuel and wood needs, the general conclusions of which have not changed substantially, draw attention to the need to exploit all sensible opportunities to develop high-yielding irrigated plantations. The substantial start that has been made has built up much experience, indicators of the species to use and others to try, and the irrigation and related technologies that should be used and refined and those to be avoided. The work of Ali, Bosshard, and Khan already cited is valuable in these respects. There is a wealth of information that indicates the courses to follow to design and implement technically viable plantation schemes once the necessary economic analyses indicate which alternatives are the most feasible. An important feature is that real benefits can be gained by integrating tree plantation with agriculture through the use of a range of shelterbelt designs. There are indications, however, that some of the developments of this type undertaken to date, particularly those making use of parcels of land that are unsuitable for annual crops, have been undertaken somewhat too haphazardly. More intensive analysis and planning, leading to careful selection of sites and design alternatives, and greater precision in aspects such as site leveling, choice of species, spacings, rotations, and, above all, irrigation quantities and schedules, as well as coppice management, would enhance production from plantations in such areas.

Kenya

A forestry component, financed by the Finnish Department for International Cooperation (FINNAID), forms part of the recently initiated Bura Irrigation Project, most of which is financed by the World Bank, on the Tana River in eastern Kenya. It is

proposed to establish 100 ha of plantations in 3 years, the principal species being *P. juliflora*, at 1.8 × 1.8 m spacing if planted or 1.8 × 0.9 m if directly sown, with *E. microtheca*, *E. camaldulensis*, and others as subsidiary species spaced at 3 × 1.25 m. Site preparation, including ridging, is done mechanically. Irrigation is by furrow from canals 500 m apart. At an early stage, it has become clear that weeding, mainly of grass, will be a major feature of development and management: it already accounts for 10% of all labour inputs. The decision was taken recently to sow or plant *P. juliflora* in the furrow instead of on the ridges so that irrigation amounts can be reduced, resulting in less weed growth. Watchmen are used to protect plantations from grazing and browsing by cattle, goats, and wildlife. Yields of fuelwood and small poles are expected from the 3rd year (M. Grut and N. Brouard, World Bank, Washington, DC, USA, personal communications, 1984).

Mali

Like the Nile and the Sénégal rivers, the Niger, with a narrow green strip adjacent to each bank, flows perennially through an otherwise more or less arid Sudano–Sahelian landscape dotted with sparse woody vegetation made up of hardy, slow-growing trees. The population is largely concentrated along the river, being attracted by the possibilities of productive activities such as irrigated rice culture and fishing. There is a serious shortage of wood to meet the needs of this riverain population for fuel for domestic purposes and, as at Mopti, for smoking fish, as well as for building. In some places, fuelwood has to be gathered and carried from sources more than 30 km inland from the villages along the river. The implications of these factors for the arid-area ecosystems are serious.

The river floods each year as a result of seasonal rainfall that begins about July, inundating the bottomland floodplains that form either narrow strips at intervals along the river, or wider inland deltaic areas. These areas are cultivated, mainly for rice production. The river water, being largely unused, evaporates, seeps away, or eventually flows into the sea. Within and on the fringes of the cultivated areas are unused areas of various shapes and sizes, usually small. These could be used to grow much needed wood and fodder, in plantations of various sizes and designs, including shelterbelts, and to protect crop and residential areas from the hot, desiccating winds. Among the areas where these possibilities exist is the 56 000-ha irrigated agricultural project area comprising an interior deltaic tract based on N'Debougou, within which about one-third of the total area is unused.

With technical and financial assistance from the International Development Research Centre (IDRC) of Canada, the Government of Mali, through the Forest Service of the Ministry of Production, initiated a 5-year program of trials aimed at determining the means for establishing forestry plantations in the area to meet the needs of the people for wood. The immediate objectives of the trials were

- To select the most appropriate species and provenances for the purposes at hand,
- To study plantation techniques suitable for the conditions of the area, and
- To determine, in general, the profitability and economic feasibility of such plantations before recommending specific methods to the land holders.

Initial difficulties stemmed from the lack of experience of the local foresters in the conduct of research trials. Also, it soon became clear that the generous watering regimes applied to the early plantings were in fact excessive and, in conjunction with a markedly fluctuating water table, harmful. This necessitated the testing of alternative,

more moderate irrigation rates. The layout and results of these trials are described here in some detail because they are not available in published form but only in project files in Mali and in IDRC's records (IDRC 1981).

The species elimination trials comprised four replications, in each case of complete randomized blocks of 25-tree plots. One trial included 17 species planted as the floods arrived in August 1976 at 2.5 × 2.5 m in 30 × 20 cm holes on the natural bottomland surface. The wide spacing permitted mechanized weeding. In a second trial, 14 species were planted on ridges raised above the floodplain surface. The statistical design was similar to that of the first trial although shortage of plants precluded the inclusion of some of the species in all the experimental blocks.

Five species were superior to all others in respect of survival and growth after 5 years (Table 1). The first two are of interest as potentially high-yielding producers of poles and fuelwood, the next two for shelterbelts and fodder, and the fifth for general purpose sawtimber.

A third trial, of 10 species, was planted on unridged bottomland at the end of the flood period in October 1977. Encouraging results were obtained from six species (Table 1). *Eucalyptus camaldulensis*, the River Red gum, which grows naturally on river floodplains in Australia, gave the best all-round results in these conditions, mean annual height growth being as much as 2.5 m and diameter growth at breast height 2.5 cm/year.

As noted, the trials tested two irrigation methods: flood irrigation on the unridged bottomlands and less inundating watering where ridges were used. Three watering rates were tested under flood irrigation: at first, rates equivalent to 400, 300, and 200 mm of precipitation per month were applied, but these were reduced to 100, 75, and 50 mm/month when it became clear that they were excessive, augerings having shown that the water table was within 0.5–2.0 m of the surface throughout the year. Survival rates were higher on the ridged sites than unridged: most of the plants on the unridged sites died in the 1st year, presumably because they could not tolerate inundation over a protracted period.

Under the particular hydrological conditions of the trial area, the trees appeared to be unable to develop root systems to any depth on unridged ground, particularly

Table 1. Partial results of two species elimination trials, Mali.

Species	Survival (%)	Mean height growth (m/year)
Second trial		
Eucalyptus camaldulensis	85	2.6
Eucalyptus tereticornis	36	1.8
Anogeissus leiocarpus	77	0.7
Dalbergia sissoo	75	1.4
Khaya senegalensis	58	1.3
Third trial		
Eucalyptus camaldulensis	65	2.0
Gmelina arborea	100	1.8
Azadirachta indica	82	1.8
Eucalyptus microtheca	82	1.8
Lucaena leucocephala	74	1.7
Khaya senegalensis	73	1.3

where inundation or a high water table was prolonged by supplementary irrigation. This factor was believed to be responsible for heavy mortality in a spacing trial planted in October 1978. Ridge planting has the advantage of enabling root-system development to take place above flood level. However, the method entails the extra cost and labour of ridging. Accordingly, a trial without irrigation or ridging was planted in the last year of the project, with encouraging early results. A shelterbelt with three rows of *A. indica* was planted in the vicinity of the project area in 1975 followed by others of four rows each of *E. camaldulensis* and *C. equisetifolia* in 1976. Survival was 80% for the first two species but the *C. equisetifolia* did not thrive.

The very positive results achieved in some parts of the trial area, combined with readily recognizable reasons for most of the failures and success when the factors concerned were adjusted in later trials, have encouraged extension of the project period to continue the search for the most appropriate species and provenances, the development of effective, practical plantation techniques, and identification of irrigation rates appropriate to the site conditions and timed in relation to the rise and fall of the water table and floods. At the same time, a move was made to encourage testing of promising species and irrigation and other cultural procedures on an operational scale by volunteer farmers working with the benefit of technical advice and nursery stock provided through the agricultural extension service. These developments have the potential to alleviate the scarcity of fuelwood and poles, as well as to ameliorate the environment through shelterbelt effects. The growth rates of the more successful young plantations are regarded with amazement by the local people. The secret of success will lie in a proper understanding of the hydrology of riverain areas of this kind and in matching species and plantation methods and designs to them (M. Grut, World Bank, Washington, DC, USA, personal communication, 1984).

Niger

Interesting research and pilot-scale irrigated plantation developments have taken place in recent years in the vicinity of Niamey on the Niger River. They are extremely relevant in the context of the inability of the natural woodland, which produces about 0.5 m^3/ha per year, to meet adequately the growing needs for domestic fuel and other wood of the city (population 325 000) without being depleted to the extent that desertification ensues.

The area is semi-arid. The Niger floods in January–February each year and low water occurs in June–July. The principal areas traditionally used for irrigation are seasonally flooded basins beside the river where the soils are fine textured, heavy, and characterized by slow percolation rates. Alluvial terraces create a second type of opportunity for irrigation but here the topography is uneven and the soil more porous and less fertile. Development costs in this type are appreciably higher than in the basins. The range of irrigation methods actually used or of potential use have characteristics that relate to the soil and topographic conditions that apply.

Irrigated tree plantation activity to date has been of two types. The first is a research phase initiated by the Centre technique forestier tropical (CTFT) and now conducted by the Institut national de recherches agronomiques du Niger (INRAN) with the support of CFTF. The second type comprises applied research or pilot operational-scale development under forestry projects funded jointly by the World Bank, the European Economic Community (EEC), and the Fonds d'aide et de coopération (FAC). The former activity has concentrated on the riverine flood basins, the latter on the alluvial terraces.

The first experimental trials, of a limited range of species, were planted in 1965 at Goudel on rich, regularly flooded river-basin soils with a water table at variable and seasonally varying depths. When the plots were harvested at 5.5 years, the mean annual increment (MAI) in terms of over-bark stem volume had been 23 m^3/ha per year for *E. camaldulensis* and 31 m^3/ha per year for *Eucalyptus resinifera*. Branch wood represented 37% more volume in each case, giving total MAIs of 31.6 and 42.6 m^3/ha per year.

Species trials were established in 1974 at Karma (mean annual rainfall 560 mm, PET 2240 mm) and irrigated with 270 mm of water from October to May. The most successful species after 2.5 years were *E. tereticornis*, *E. camaldulensis*, and *D. sissoo* followed by *E. resinifera*, *A. indica*, and *A. nilotica* var. *nilotica*. Appreciably less successful were *E. microtheca*, *Eucalyptus alba*, *Eucalyptus deglupta*, *A. lebbek*, and *C. equisetifolia*. A provenance trial of *E. camaldulensis* was conducted at the same time. After 3 years, MAIs of the eight provenances varied from 7.8 to 20.0 m^3/ha per year, total volume.

In an unreplicated test of three irrigation rates (0, 270, and 460 mm/season), MAIs after 3 years were 4.6, 12.1, and 12.9 m^3/ha per year respectively, indicating that, in the two irrigated treatments, the tree roots were probably down to the water table.

At Lossa (550 mm annual rainfall, PET 1850 mm), a flood irrigated spacing trial of *E. camaldulensis* was initiated in 1975: 400 mm of water were applied over 18 months. At 2 years, MAIs in terms of solid volume equivalents of stacked wood decreased with increased spacing (Table 2).

Also at Lossa, a trial to compare three rates of localized irrigation with no watering, using the technique of the Société d'exploitation des techniques de l'irrigation (SETI)/Bas-Rhone, was initiated in 1978 on the light soils of the alluvial terraces. The rates of irrigation combined with the rain that fell were in no instance more than 32% of PET. For this reason, no significant differences in growth were observed between treatments after 3 years. Growth on these infertile, porous soils was poor and the root systems occupied small volumes of soil. A nearby trial of shelterbelts planted on the raised levees between flood irrigation basins resulted in more impressive growth. This was taken to demonstrate the importance of selection of irrigation method, because root development was more widespread, and because of the benefit of soil working in the basins (Barbier 1977, 1978; Delwaulle 1979; Barbier and Louppe 1980; Hamel 1985).

Encouraged by the results of these early trials, the World Bank decided to support an applied research project to develop irrigation procedures in a 400-ha 2-year project (subsequently reduced to 240 ha) for application on an operational scale. The

Table 2. Solid volume production of an irrigated spacing trial of *Eucalyptus camaldulensis*, Lossa, Niger, 1976

Spacing (m)	Mean annual increment (m^3/ha per year)
1 × 1	38
1 × 2	27
1 × 3	24
2 × 2	22
2 × 3	19
3 × 3	16

area selected, 35 km northwest of Niamey, was on the first of the lower river terraces, some 15 m above the river, between the bottomlands of Namade-Goungou and a nearby chain of sand dunes. The relief, variable sandy soil, hydrological characteristics, and high cost of earth moving on this rolling terrace area would not permit the use of traditional flood or furrow gravity systems of irrigation. Accordingly, two systems by which water is transported under gravity through pipes were used. Of the two areas established in the 1st year, one covering 100 ha used the low-pressure gravity "California" irrigation system by which water is distributed to percolation depressions at the bases of planted trees by narrow concrete channels and short lengths of polyvinyl chloride (PVC) piping. The other was a 35-ha development using the SETI/Bas-Rhone localized irrigation system, which had given promising early results (already mentioned) at Lossa. This system was also used for a 105-ha extension of the program in the 2nd year.

Numerous difficulties were encountered in the early stages of this work. They stemmed partly from the initial lack of experience of local staff in handling specialized irrigation and other equipment, partly from the need to adapt the systems under development through several stages to the local ground and soil conditions, and partly from clogging of filters and finer pipes by sand, but principally from the difficulties and breakdowns that attended the various methods attempted to pump water out of the river, all but the last of which had to be discarded. The method eventually retained was to use a submersible pump anchored to bedrock in the riverbed. Earlier efforts to use a pump on a raft, delivering water through a flexible pipe, had proved impracticable. Variable and sometimes poor plantation development resulted from irregular, uneven, and sometimes excessive watering, the use of genetically poor seed, poor root development (particularly when it was confined to the immediate vicinity of the piped water sources), and the poor nutrient status of the soil. Growth rates approximated 3 m^3/ha per year under localized irrigation, which was disappointingly low. Under the "California" system, growth was twice that rate. The importance was demonstrated of ensuring full early occupation of the site in the interests of efficient use of water and optimum production. Nevertheless, it was encouraging that good stands of *E. camaldulensis* were established in some areas, their heights being 6–8 m after 2 years. Soil or water salinity have not been problems except in brackish areas, which, however, are clearly indicated by the growth in them of the dwarf doum palm.

The direct investment and operational costs of these trials were inevitably high in view of the trial-and-error approach used in some phases and the small area of the plantations. Those for localized irrigation under these conditions were 50% higher than for the "California" system.

It was concluded that, given stability of the overall system used, an average overall production rate of 10 m^3/ha per year would be sustainable. In view of the prices that can be expected for fuelwood and poles in relation to the costs of production, however, and because of the overriding claims for land for agricultural production, it became clear that tree plantation should be undertaken on the basis of integration with irrigated agriculture.

Accordingly, since 1982, new work has been devoted to the integration of tree planting with irrigated agriculture in the riverine flood basins where, as already noted, the soils are quite different and there is a water table within reach of tree roots, partly as a result of irrigation of the agricultural crops. Pilot-scale trials planted at Sebery, Kolo, and N'dounga in 1982–83 consisted of single-row windbreaks of *E. camaldulensis* along access paths, canals, and drains. Optimal development of these plantings was hampered by a lack of concern by the farmers who are unaccustomed to such activity.

In 1983–84, tree planting under localized irrigation, sufficiently heavy and for periods sufficient for the roots to make contact with the water table, was undertaken at Namade-Goungou. Pockets of land within the farming areas are being used that, because of topographical or soil features, are unsuitable for agricultural cropping. Development is based on 16-ha modules. Attention is being concentrated on such aspects as the regulation of quantities of water applied in relation to local water table features and rainfall amounts, planting date, the quality of nursery stock, and provenance of seed. Spacing is varied according to whether the planting is of pure tree plantations or involves a degree of integration with annual or perennial forage crops. Prominent among the species used are *E. camaldulensis*, *Borassus aethiopicum*, *Acacia holosericea*, and *Khaya senegalensis*.

Drawbacks to the use of pockets of land unsuitable for agriculture are similar to those already discussed in relation to practice in the Sudan. Also, such areas are unlikely to represent more than about 5% of the agricultural areas so that total wood production will be small in relation to the needs. The importance has been stressed of ensuring that the farmers concerned in integrated agricultural and tree production understand that their active, permanent participation is essential for success. Also, there is a priority research need to develop operational methods appropriate to both riverine flood basins and alluvial terraces (Hamel 1985; J. Gorse, World Bank, Washington, DC, USA, personal communication, 1984).

Nigeria

An interesting plantation trial involving irrigation in the 1st year was initiated by R. Fishwick (World Bank, Washington, DC, USA) in the 1960s at Mallam Fattori on permeable lacustrine sands some 30 km from Lake Chad in the extreme northeast of Nigeria where tree plantations cannot be established under natural conditions. A provenance trial of *E. camaldulensis* was irrigated by rotating sprinklers during the 1st year until the tree roots reached the water table. On the flatter, lower lying areas, growth, particularly of 'Petford' and 'Katherine' provenances, was remarkable, being described by Pryor (1970) as the fastest recorded for any *Eucalyptus* species: 11 m tall and over 10 cm in breast height diameter (DBH) at 17 months. The MAI of the fastest growing provenance was 21.8 m^3/ha at 4 years (Jackson 1976; Allan 1977). More recent growth assessment results are not known.

Sénégal

The Sénégal River basin comprises the Delta (extending 140 km upstream from the mouth) and the Basse, Moyenne, and Haute Vallée zones based on the towns of Podos, Matam, and Bakel respectively. Its bed has an almost imperceptible fall over hundreds of kilometres with the result that it floods an enormous area each year, the peak of the floods occurring between July and October. Not only do the floods vary from year to year and water levels over the floodplain vary greatly within any one year, but at low water the river is invaded over a great distance by the ocean, which results in an undesirable admixture of saline water. Regulation of the flow of the river and exclusion of seawater will be achieved through a series of barrages now under construction.

The basin is an important rice-growing area. There is thus a tradition of irrigation, the schemes varying from highly organized large ones in which water for flood irrigation is delivered by canals ultimately to parcels of about 0.7 ha and farmers are organized in groups of 20–30 families, to less stable small village schemes on higher ground supplied with pumped water, and even less stable units that have subsisted by

capturing floodwater and impounding it behind automatic gates. The soils over the more frequently inundated parts of the basin are finely textured, hydromorphic alluvium that is usually saline, with some sodium content. The fuelwood and other wood needs of the 600 000 people who live in the river basin, and of the 800 000 people in Dakar, 300 km to the south, have so far been met from the overused, fast-disappearing natural woodland in the region, which grows at less than 1 m^3/ha per year.

In view of the large demands for wood and having regard to the measures in progress to stabilize the flow and annual flooding of the river basin, research on irrigated forest plantations has been undertaken since 1980 by the Institut sénégalais de la recherche agricole (ISRA), funded by FAC. The results and conclusions to date are summarized here, based on Hamel (1985).

Tree planting trials without irrigation resulted in inadequate and variable survival rates, indicating that rainfed planting is feasible only along canal sides.

Trials with light, mobile sprinkler irrigation equipment led to better survival but variable growth. It was concluded that the method can be useful to enable tree roots to reach the water table or for intercropping of tree with agricultural or pasture crops. However, the method is not generally suitable for tree growing in these conditions. Flood irrigation requires careful leveling and is thus costly. It is suitable for trees grown along interbasin ridges and would be appropriate also when trees are grown in dense stands. Localized irrigation (goutte à goutte or SETI/Bas-Rhone systems) would be useful to control water applications when water is scarce or in porous soils. Furrow irrigation, permitting slow percolation, is probably the best system under local conditions: it is simple to install, operate, and maintain. An important drawback, however, is the difficulty of gauging how much water is applied, although in heavy soils this is facilitated by using small profile furrows.

Fourteen *Eucalyptus* species have been tested, present indications being that *E. camaldulensis*, *Eucalyptus brassiana*, *E. tereticornis*, *Eucalyptus jenseni*, and *Eucalyptus argillacea* are the most suitable. *Eucalyptus microtheca* is very variable and the others are slow growing. Provenance trials of *E. camaldulensis* and *E. microtheca* were established in 1984. Of seven *Acacia* species tried, *A. holosericea* had the best growth, being almost as rapid as the eucalypts whereas *Acacia radiana*, *A. nilotica*, and *P. juliflora* were slower. *Leucaena leucocephala*, of which four provenances are under trial, appears to be well adapted to local conditions and growth rates approximate those of the better eucalypts. The foliage is abundant and so is natural regeneration: the latter feature may be a warning that the species could become a weed. *Parkinsonia aculeata* and *K. senegalensis* are promising, as is *Gmelina arborea*; *Melaleuca* species and *A. indica* are not promising. The fruit trees most highly recommended are date palms, bananas, *Zizyphus* species, grenadillas, and papayas.

The results of silvicultural technique studies emphasized the importance of good nursery soil mixes, wetting plants and the planting site before planting, and planting when conditions are warm and humid, i.e., at the time of arrival of the intertropical convergence zone.

Recently established trials relate to tree spacing, amount and frequency of watering, use of fertilizers, date of coppicing, and shelterbelt designs.

The whole approach emphasizes the belief that tree planting, to be economically viable, must be integrated with agriculture. For best results, it must be included from

the beginning — adding it after the agricultural phases have been planned and implemented is a severe handicap (Hamel 1985).

Zimbabwe

Empirical trials comprising 138 unreplicated plots representing 45 species of 13 genera were established in 1959, 1965, and 1966 under irrigated conditions in the Zimbabwean low veld, an area of high average temperature and low, erratic, seasonal rainfall. Barrett and Woodvine (1971) described the trials and summarized the results. These showed that, although growth was variable, it was remarkably rapid in many cases.

The trials were located on two estates that were developed, largely from 1959 onwards, for irrigated agricultural production in an area of about 425 m altitude at 21°S 31°5′E. The area falls within Silvicultural Zone V (Barrett and Mullin 1968), which is unsuitable for exotic plantation species except under irrigation. The soils are moderately shallow to shallow, brown or reddish brown, sandy to sandy clay loams derived from gneiss, with pH values in the range of 5.5–7.2. Rainfall varies from 250 to 750 mm/year and short periods of humid cloudy weather occur at any time of the year. Abundant sunshine and moderate to low humidities provide good conditions for free evaporation even in the hottest months.

Evaporation rates can exceed 12.5 mm/day during the hot weather. Precipitation deficit is correspondingly high at 1250–1500 mm. Wind speeds average 8–11 km/hour in the driest months to 4–7 during the wettest. Maximum temperatures in excess of 32°C occur throughout the year and they commonly rise above 40°C in the summer. There are 3 months of cool weather with mean maxima around 25°C and mean minima of 6–10°C.

Trial sites were selected as being representative of those likely to be available for tree plantations in the agricultural irrigation projects. They included strips of land along canals and small areas of unused land throughout the irrigated fields of sugarcane and other crops, most of them subject to a more or less continuous supply of underground seepage water, although one or two of them were somewhat droughty, at least seasonally. The various sites used were characterized as to nature of irrigation influence and grouped into six categories for analysis. All plots were watered, either by hand or flood irrigation, during the first few months after planting, after which most of them were left to subsist on whatever seepage water was available.

As far as possible, site preparation was by plowing and harrowing but, in some cases, holes were dug, as much as 60 cm deep and 45 cm wide. Plant spacings varied from 2 × 2 to 2.4 × 2.4 m. Irrigation allowed considerable flexibility in the choice of time of planting, which was done at various seasons depending on the availability of labour. Polythene tubes, when used, were removed at the time of planting. Survival rates were very high, with 100% success being common. Deaths occurred in some areas after postplanting irrigation ceased. Termite damage, when it occurred, was thought usually to be a contributory rather than the sole cause of death. Weeding was intensive.

Assessments and measurements were done periodically from planting time onward using standard, defined procedures. The parameters assessed included height, DBH, stem straightness, apical dominance, type of branching, and presence or absence of flowering. Results, including MAI and basal area per unit area, were given on the basis of measurements made when the plots were 4 years and 5 months to

5 years and 8 months of age (53–68 months). The coniferous species tried (*Araucaria cunninghamii*, *Pinus elliottii*, *Pinus halepensis*, *P. radiata*, and *Pinus taeda*) proved unsatisfactory in most respects. The greatest successes were achieved with *Eucalyptus* species, of which a large number were tested, the most successful being *E. camaldulensis*, *Eucalyptus grandis*, *Eucalyptus punctata*, *E. resinifera*, and *E. tereticornis*. Mean annual increments as high as 65 m^3/ha at 68 months were recorded. Moderate yields were achieved with *Populus deltoides*, *Grevillea robusta*, *Tectona grandis*, *G. arborea*, and *Casuarina cunninghamii*.

One log from each of 16 promising species was used in sawing tests and for examination of basic density and fibre length. The butt log in each case was sawn into boards that were air seasoned. Some working properties, e.g., peeling and production of match splints, were investigated for some species by a match company. General comparisons with material grown under rainfed conditions indicated that the material from the irrigation plots appeared to be quite acceptable for a wide range of uses, including transmission poles, sawtimber, and peeler logs.

The report on these valuable trials concludes with an economic analysis that gives the results some practical perspective and confirms that irrigated forestry within major irrigation schemes in the region could be a feasible proposition.

North America

United States of America

A survey was undertaken among about 150 industrial forestry companies throughout the USA to ascertain the extent of application of intensive forest production practices, including irrigation. Of the 109 firms that returned the questionnaire, none had practiced irrigation in 1971–74 although 6% of them signified their intention to do so during the succeeding decade. The expectation of added gain in the national harvest that could result from irrigation (1 of 11 possible intensive cultural practices) varied widely but averaged 13% (De Bell et al 1977).

Two irrigation studies were undertaken to determine whether the growth of planted *P. deltoides* could be increased by irrigation during the growing season in the North-Central states. In one study, water was being applied daily with sprinklers, in the other, in furrows when the plants needed it. A secondary objective of the latter study was to ascertain whether irrigation improves the effectiveness of soil-applied systemic insecticides. First year results of the sprinkler study showed that late-summer irrigation was most beneficial to height and diameter growth. In the furrow irrigation study, in which it may be assumed that watering rates were low, growth was not increased although effectiveness of insecticide application was (Belanger and Saucier 1975).

Alverson (1975), in a thoughtful analysis, reviewed issues, choices, and actions regarding the use of wastewater (sewage effluent and the like) for irrigating Douglas-fir and western hemlock forests in the Pacific Northwest, a possibility that has been of interest to industrial forestry companies and civic authorities in that region, and others, for two or three decades. He drew on published results of research by the Weyerhauser Company (Woodman 1971, 1973) to illustrate that irrigation (in this case by sprinklers above the canopy), both alone and combined with fertilizing or thinning, or both, can significantly increase production. However, he noted the importance of ascertaining whether any constituents of sewage effluent can have harmful effects on the species or sites concerned, e.g., effects of chlorination of water, chemical and

biochemical oxygen demand, suspended solids, total phosphorus, bacteria, viruses, or heavy metals. Also, he speculated upon the public acceptability of such practice and the extent to which it might limit recreational use of treated areas. He noted that high capital and operating costs might rule it out. These considerations should be weighed against the fact that the alternative to land disposal of these wastes is high-technology, high-cost treatment.

The effects of irrigation with and without the application of sewage sludge were tested on red alder and black cottonwood in the Pacific Northwest. Irrigation increased survival in both cases but added sludge decreased both survival and height growth of black cottonwood and height growth of red alder (De Bell 1975).

Although the paucity of literature on the subject suggests that tree plantation is of little if any interest in the extensive irrigated agricultural areas in California, Arizona, and the Colorado Valley, it is pertinent to note that salinity problems are widespread and are of great concern in the area. Controlling them entails the installation of drainage and leaching with sweet water (Eckholm 1975; Pillsbury 1981).

South and Central America

As for North America, there appears to be little published information on irrigation forest plantation practice per se, although irrigation is widely used in some areas and *Eucalyptus*, *Populus*, and *Salix* species, for example, are grown in shelterbelts in irrigated agricultural lands in several countries.

In Argentina, poplar and willow growing is concentrated in the Parana delta where some 100 000 ha are under plantations of these trees and, in areas where agriculture is centred, such as Mendoza and Rio Negro, where they are integrated with agriculture in various ways (FAO 1979b). It is reported that some 300 000 ha of the same tree types are grown under irrigation on the Rio del Plata. The tree materials used commonly include *P. deltoides* and *P.* × *euramericana* clones, including many selections from breeding selections in Europe. Yields on the best sites are of the order of 18–34 m^3/ha per year at 16 years and on poorer sites 10–22 m^3/ha per year (C .retero 1972).

In Peru, under a project funded by the U.S. Agency for International Development (USAID), irrigated *Prosopis* plantations are grown successfully in a 1000-ha tract of shifting sand dunes in the desert area near Piura in northwestern coastal Peru. Glacial melt water is used for irrigation at a rate of 300 mm/year, which contrasts with 1000–4000 mm used for agricultural crops in the area. Yields include fuelwood and 6–7 t/ha per year of high-protein cattle feed (USDAFS 1980). *Eucalyptus globulus* is one of the principal economic resources of the peasants in the valley of the River Mantaro where planting began in the 19th century. There are now some 8000 ha in rows round fields, many of which are irrigated (Bohorquez Rejas 1972).

In Uruguay, there were some 3000 ha of plantations mostly of *P. deltoides* but also including *P.* × *euramericana* hybrids and willows (FAO 1979).

Waterlogging and salinity are problems in the coastal irrigation lands of Peru, where one-third of them are affected, and in Argentina where 20–30% of agricultural irrigation lands in Patagonia are affected by salt. The problem is also serious in poplar-growing areas along the Colorado River in La Pampa Province. In northeastern Brazil, more than half of the irrigated land is affected by waterlogging and salinity. In northwestern Mexico, huge irrigation schemes are being affected due to inadequate

drainage or because the available water is used too sparingly in an effort to spread it more widely: 80% of the land in the Colorado River Delta is affected (Giunchi 1972; Eckholm 1975).

Australia

Trials of land disposal of municipal, pulpmill, and winery effluents compared with irrigation using river water were undertaken in warm climate conditions in Northern Victoria. They were established at four locations in 1972, 1973, and 1976, covering a range of soil types from deep sandy loams to very heavy clays. Overland flooding using check banks was done in accordance with local experience of irrigating pastures. In the first trial, 13 *Eucalyptus* species, *C. cunninghamiana*, two poplars, and *Salix vitellina* were tested on three soil types using normal irrigation water. Six species were consistently superior in terms of survival and height growth with both forms of irrigation water and, with variations, across the range of soils covered in the trials. These species were *E. camaldulensis*, *Eucalyptus botryoides*, *Eucalyptus saligna*, *Eucalyptus globulus*, *E. grandis*, and *C. cunninghamiana*. These results were used for the selection of species to be used in a series of new trials in various parts of the state in which survival, height growth, tree form, and wood quality were to be assessed. The new trials were intended to test the effects of different quantities and qualities of effluent on soil characteristics and on the growth of tree crops, and to ascertain the fate of the effluent elements.

The most recent trials established included a test of irrigation with pulpmill waste on the growth of 16-year-old *P. radiata* as well as tests of series of provenances of *E. camaldulensis* (13 provenances), *E. globulus* subsp. *globulus* (10), *E. saligna* (3), and *E. grandis* (5). From a very early stage, provenance differences exceeded those between species.

In all these trials, site preparation was by deep plowing, with ripping along the planting lines where the soil was poorly structured or included horizons that impeded drainage or rooting. The plowing was followed by repeated disc cultivation over several weeks to reduce the serious weed growth before planting. This was supplemented where necessary by using knock-down herbicides such as Glyphosate[2] or Propazine (to which *Eucalyptus* species are sensitive) well before planting. Nitrogen, phosphorus, and potassium fertilizer was applied at 40 g/plant at the time of planting to help the trees to overcome early weed growth. Spacing was 3 × 1.5 m which permitted mechanical weeding, an operation that had to be carried out as many as six times during the year after planting (Edgar and Stewart 1979).

An irrigation trial near Canberra was initiated in a 15-year-old *P. radiata* plantation that was normally subject to stress due to low summer rainfall, a characteristic of the local climate. Diameter growth and wood characteristics were assessed after 11 years of irrigation when the trees were 26 years old. Irrigation increased diameter growth and maximum wood density although overall density was scarcely affected. Detailed effects on wood anatomy are described in chapter 6. These results confirmed the trends toward increased rates of diameter growth and proportion of thick-walled cells associated with summer and autumn growth that had been found in a similar, earlier trial near Adelaide in South Australia (Nichols and Waring 1977).

[2] Mention of trade names is for the purpose of information only and does not imply endorsement of the product.

Conclusion

Irrigation is practiced for the most part to enhance agricultural production from both annual crops and perennial fruit crops. Tree crops to produce wood account for a very small proportion of the land under irrigation: even in the Indus Valley of Pakistan where irrigated forest plantations have attracted much attention, they represent not more than 1.5% of the total irrigated area.

The global area under irrigation for all purposes is estimated to total about 200 million ha. This represents 40% of the area potentially available for this purpose. There are many reasons why more land is not cultivated in this way: one of them is scarcity of water, another is the high cost of developing irrigation water supplies, yet another is the high capital cost of developing irrigation schemes themselves, including the drainage works that are necessary to sustain the productivity of such projects in the long term.

The history of irrigation over thousands of years in ancient centres of civilization emphasizes the awesome implications of inadequate control over the distribution of water and its application to crops. This has led to the destruction of production systems through the now familiar pattern of vertical and lateral seepage, rising water tables, induced soil salinity, and, finally, declining yields and total crop failures. Whole civilizations have been brought down by such sequences of events. Some of the lands affected are still out of production even though hundreds or thousands of years have passed since they were abandoned. The cost of reclamation is high. In many cases, prevention of the sequence of events described is possible only if effective control and coordination are applied throughout the syster.., from the responsible agencies of government, through all the levels that apply, down to the individual farmer or forest employee who opens and closes the valve that lets water into the field. Where the river system extends through more than one country, control and coordination must be exercised at the international level as well. History has shown that the alternative can be ultimate disaster.

The review of irrigated forest plantation programs in many countries emphasizes the need for a high degree of professionalism and skill in planning, designing, implementing, managing, and organizing such schemes. Too often, it appears that these ingredients for success are deficient. In view of these needs, and the challenging, often virtually intractable physical, chemical, and biological factors entailed over the long term, it is clear that the staff concerned, at all levels, must receive appropriate training, should work according to unequivocal management arrangements within properly conceived and established organizations, and should have the physical resources and the time that are required to do the job properly. Individual farmers require technical guidance through appropriate extension activity.

The notion of irrigated tree plantations is attractive in hot, dry climates because of the high growth rates that can be achieved. The attraction is greatest in arid areas where trees, particularly if they are the major source of building poles, domestic fuel, and fodder, are scarce, and prices for these commodities high. Tree crops of various designs are frequently, and logically, integrated with irrigated agriculture. Under such conditions, they can be very profitable, even before the value of their physical environmental benefits is taken into account. There is scope for much more widespread initiatives of this kind, particularly the use of shelterbelts to enhance agricultural yields and ameliorate the environment in general while, at the same time, producing appreciable quantities of wood and other tree products.

Wood production from irrigated uniform plantations has increasingly come to be regarded as not being feasible, principally on economic but often also on sociological grounds. The trend is, therefore, strongly toward integration of tree crops in various ways with agricultural production. Integration of this kind often takes the form of plantations on relatively small parcels of land not required for agriculture and along roads and canals. Although this is sensible, it should be recognized that the reasons why odd areas of land are not used for agriculture can apply also to tree crops, with the result that their performance may be suboptimal. Also, in areas of wood scarcity, planting on this scale might not represent, alone, an effort of sufficient magnitude to meet the needs. The development of large-scale block plantations may be economically feasible where reliable supplies of industrial, municipal, and other wastewater are available.

A successful irrigation project clearly depends upon thorough planning, surveys, and analyses of all features and factors that can affect the scheme, and sound technical design before large-scale development is attempted. Field trials and small-scale pilot schemes should be used whenever there is doubt about the species, methods, or watering regimes to use. Proper attention to sociological aspects, and well conceived organization and management structures and procedures are necessary for success.

4. Some Basic Concepts

The growth of plants under irrigation is governed by a complex of interacting physical, chemical, and biological factors and processes that are more or less profoundly influenced by the design and operational features of the systems adopted. Although many of them are of more concern in research and developmental phases than in implementation and operation, it is important for the practitioner to bear them in mind so that important underlying principles are not ignored. They are briefly reviewed here in terms of plant–soil–atmospheric water relationships and irrigation in relation to soil properties, topography, and hydrological features.

Plant–Soil–Atmospheric Water Relationships

Doneen (1972) defined irrigation and its management and manipulation of water–soil–plant relationships. The nature of these relationships, and of atmospheric influences, as well as the processes involved, are the subjects of a considerable scientific literature, much of it summarized by Fuchs (1973a–c), Gairon (1973), Gairon and Hadas (1973), Hadas (1973a, b), Plaut and Moreshet (1973) and applied in the water evaluation guidelines given by Ayers and Westcot (1976).

Soil water is subject to various mechanical or molecular forces that arise from gravity, the presence of solutes, and the interaction between water in the soil and the walls of the spaces within which it occurs. These forces cause the water to be adsorbed, retained, transferred within the soil medium, drained or evaporated from it, or taken from it and transpired by plants.

Water may enter a soil profile by infiltration from above after flooding, sprinkling, or rain; from a water table from below; or horizontally. These water movements are affected by soil texture and structure. When water application exceeds infiltration capacity, the excess will start ponding, which may be followed by runoff or flooding. The amount of water held in the soil after the excess has drained away is known as the field capacity, which is usually reached 2–5 days after irrigation ceases.

The infiltration and water-holding capacity of a soil are affected by its texture and structure. General soil water-holding capacity and water-intake data are given in Table 3.

Table 3. Generalized water-holding capacity and intake rates by soil types.

Soil type	Water-holding capacity*	Intake rate (cm/hour)
Sandy	2.5	3.8–7.5
Silty	5–6.5	0.8–2.5
Clay	4–6	0.3–0.8

Source: Thomas et al. (1981). * Centimetres of water per 30-cm depth of soil.

When soil water is depleted through evapotranspiration, the point is eventually reached when plants begin to wilt. Soil water content at the point when older leaves will not recover from wilting, but young ones will, is termed the incipient wilting percentage; when the whole plant wilts permanently, it is known as the permanent wilting percentage.

Water uptake by plants depends on the characteristics and dynamic status of water in the soil, water in the plant, and on the nature, extent, and efficiency of the plant root system. Root development is affected by a number of factors that can be ameliorated by cultural practice: soil density and compaction, soil water and oxygen availability, and availability of nitrogen, phosphorus, and potassium.

The driving force for transfer of water from the soil into the root cells is taken to be the water potential gradient between the soil water and the water at the root surface. Water moves in the soil toward a root along a gradient of decreasing water potential. The plant absorbs water in the liquid phase to maintain its tissues in a saturated condition while it loses water by evaporation from the leaf parenchyma cells through the stomata and cuticle to the atmosphere.

Thornthwaite and Hare (1955) explained evapotranspiration on the same dynamic basis as evaporation. They indicated how these concepts and that of potential evaporation make it possible to use climatic data alone to predict soil moisture condition and values for moisture surplus and deficiency. When soil moisture is at field capacity, actual and potential evapotranspiration are the same and precipitation in excess of PET becomes water surplus. When precipitation is less than PET, the difference is made up from soil moisture storage, the amount of depletion of which is the soil water deficit.

Irrigation and Soil Properties

Soil is a complex comprising a liquid phase, a gaseous one that provides essential aeration, and a solid phase made up of a mineral portion and a small but biologically important organic one.

Soil texture is determined by the relative proportions of sand, silt, and clay. It governs infiltration and soil water-holding capacity and thus determines irrigation frequency and amounts. Soil structure refers to the arrangement and adhesion of soil particles to form aggregates. It influences permeability, storage of water and air, and root penetration. Soils with crumb or granular structure are preferred for irrigation. Structure can be affected detrimentally by compaction, cultivation when wet, or excessive cultivation. It deteriorates when sodium salts build up and break down or disperse clay aggregates. This lowers infiltration rates and can render soil virtually impermeable (Ali 1960; Doneen 1972; Yaron and Vink 1973).

Soil chemical features in relation to irrigation are reviewed and discussed by Bresler (1973), Kalkañ (1973), Meiri and Levy (1973), Shainberg (1973), and Yaron and Shainberg (1973). Such features reflect the dynamic relationships among exchangeable ions in soil colloidal solutions. Irrigation with, for example, poor quality water can disturb these relationships and adversely affect soil chemical characteristics. Thus, watering with saline water can result in replacement of calcium and magnesium, which are normally the principal cations present, with sodium. This affects the soil structure, breaking down the aggregates, and thus reducing infiltration and permeability.

Water-soluble salts in the soil medium move by diffusion from points of higher concentration to areas of lower concentration. Dissolved ions carried by water movement are said to undergo convection, the velocity of which is influenced by the distribution of pores of different sizes and shapes. Changes of soil water content as a result of infiltration, redistribution, evaporation, and transpiration bring about the simultaneous movement of water and solutes. The availability of nutrients to the crop is related to the exchange properties of the soil and the movement of solutes.

In the soil, nitrogen is continuously consumed and excreted by soil organisms and plants. Most ammonium nitrogen is in the form of exchangeable ions on the clay and organic material. All nitrogen of the nitrate form, which is readily transported in the soil, is available for plant use.

Potassium occurs in the soil in fixed form in feldspars, micas, and clay minerals, in exchangeable form on clay minerals, and dissolved in the soil solution. The latter two forms are readily taken up by plants. Potassium tends to lag behind the soil wetting front and downward movement is restricted to a few centimetres per year.

Most soil phosphorus occurs in the solid phase as slightly soluble calcium phosphate or adsorbed on clay particles. Due to their limited mobility, most added phosphates are concentrated in the upper soil layers.

The response of a plant to an increased supply of a nutrient is linear, provided that this factor is the only one in short supply and limiting yield. When crop production is evaluated in relation to fertilization under irrigation, it is important that total dry matter production is the parameter used. Under a given amount of irrigation water, fertilization can increase the transpiration ratio as much as threefold.

Irrigation and Topography

Topography is a major factor in the selection of irrigation method and in system design, operation, and cost. It affects hydrological processes such as runoff, infiltration, sedimentation, and drainage. Through these, it affects soil-forming processes by influencing the distribution of water-transported materials, the movement of solutes, and the illuviation of clay materials. However, visible topographical features alone cannot be used to deduce subsurface water-movement patterns because, particularly in floodplains, major barriers to underground drainage can be hidden under sediments.

Topography, through its relationship with gravity, is an underlying force in irrigation systems, particularly the so-called gravity systems in which the distribution of water is controlled by the land surface itself and not by mechanical devices. In such systems, topography acting with soil characteristics influences design. Thus, the finer the soil texture, the steeper is the gradient of slopes over which water can flow without eroding the surface; the less the slope and the finer the soils, the longer can furrows be without infiltration being excessive toward the input end (Kramer 1949; Rawitz 1973b).

The extent to which the slope of land can reasonably be changed by land grading, which is costly, is limited (Doneen 1972; Rawitz 1973b). Reference was made in chapter 3 to the difficulties that beset the development of plantation irrigation arrangements on undulating ground on the terraces of the Niger River. An effort was made to avoid earth-moving costs by aligning water channels or pipes along or close to the contours. However, this resulted in much wastage of land within the plantation area. The use of trickle irrigation in such conditions was more successful because this system can, up to a point, accommodate undulating ground.

Hydrological Implications of Irrigation

The impact of irrigation on a landscape, particularly an arid landscape, implies major changes in the hydrological cycle. Inputs of water no longer arise as a result of occasional rainfall, much of which is normally lost through evaporation, leaving little or none to recharge groundwater. The irrigation water, whether finely or crudely tuned to crop needs, carries sediments and chemical constituents from its source or areas through which it has flowed.

If movement of excess infiltrated or floodwater out of the area is impeded, the water table would rise, waterlogging could follow, bringing dissolved salts to the upper soil horizons. Crop performance would decline due to lack of soil aeration, accumulation of salts, or both. In effect, this is what happened in the Tigris and Euphrates valleys and, more recently, in the Indus Plain (as was referred to in chapter 3). What should happen is that water should not be applied in amounts in excess of crop and periodic soil-leaching requirements, and inadvertent excess quantities of water, including rainfall, as well as leachates, should be led out of the area by subsoil or surface drains, assisted by pumps when necessary. If necessary, irrigation water should be treated to reduce its salt content.

As was noted in chapter 3 while discussing countries in South Asia, the Middle East, and the Mediterranean region, saline water can be used for irrigation. However, as the Tunisians know, this is sustainable only if the rooting zone is kept moist so that salts do not accumulate in it but are leached to its margins, or leached out of the zone when sufficient clean water becomes available for the purpose in the form of rainfall. Underground water must never be permitted to build up.

Irrigation imposes unnatural conditions and processes on the landscape. The undesirable ones must be countered by quite specific measures, of which drainage is usually one. It should be built in from the beginning. Without it, either the project will fail or costly reclamation measures will be necessary.

5. Irrigation Systems

The purpose of an irrigation system is to convey water from a source to the irrigation area and to deliver it to the root system of the crop. If well designed and operated, it will meet three requirements: assurance of a sustained maximum economic return, minimal loss of water during conveyance and application, and maintenance of production by preventing erosion, soil structure degradation, development of soil salinity, or raising of the water table. Because many factors interact to achieve these requirements, there is no ready-made system for application in each particular instance: a system must be designed or adapted to suit the factors that apply in each case — extent and type of water source; quality of water; depth and quality of groundwater; costs of equipment; site conditions, preparation, and labour; and the availability and skill of the personnel available. The principal methods used are irrigation based on gravity flow, sprinkler systems, localized systems, and certain special systems. There are alternative classifications of irrigation systems, for example those of Booher (1974) and Vermeiren and Jobling (1980) who recognize two groups.

The first group comprises systems that cause wetting of the whole soil surface in the field irrespective of the organization of the crop. These systems are subdivided into underground systems that control the level of the water table and systems that supply water to the soil surface either by gravity, as in flood or border irrigation, or by overhead pressurized pipes as in sprinkler irrigation.

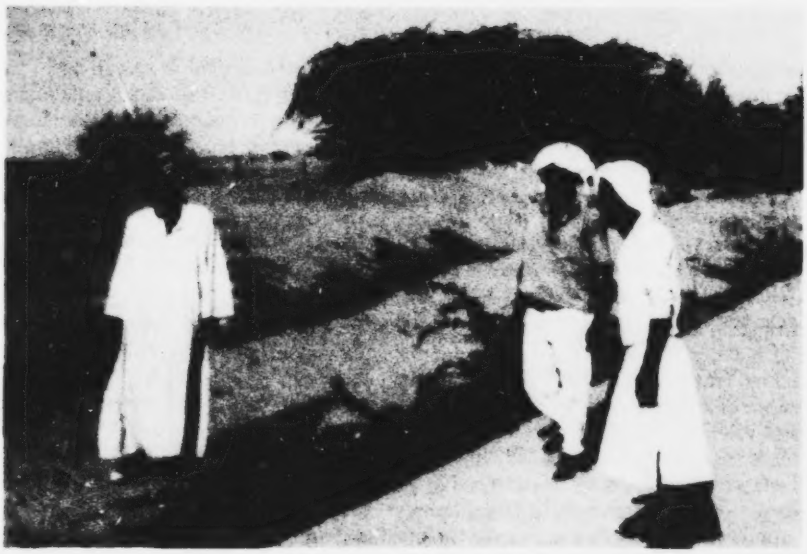
The second group consists of systems that cause wetting of only part of the soil. These are subdivided into underground systems using low discharge piping (subsurface irrigation) and surface-application systems, either by gravity (as in basin or furrow irrigation) or by overhead pressurized pipes.

In this chapter, these systems are briefly reviewed and outlined in relation to forest plantation irrigation. Classification is used here purely as a matter of convenience.

Gravity Systems

In gravity systems (see, in particular, Bosshard 1966a; France 1969, 1977; Rawitz 1973b; Booher 1974), the ultimate distribution of water is controlled by the land itself and not a mechanical device. The extent to which the land surface can be changed is limited by cost and physical factors, including the implications of disturbing the soil.

Surface irrigation systems are characterized by the manner in which the irrigation stream is controlled by the soil surface. There are four types: wild flooding, border check, basin, and furrow irrigation.



Furrow irrigation near Dongola in the Sudan: Irrigation of Eucalyptus *recently planted along the sides of furrows.*

Wild flooding is the least efficient and least commonly used. It is principally used on perennial pastures and hay crops that protect the soil from erosion. Water is turned out at frequent intervals (2–3 m apart) from a graded supply ditch along the upper side of the field and allowed to flow freely down the slope. A minimum of land grading is required and once properly established the system requires minimal labour to operate it. The system is inappropriate for application to forest plantations because efficiency in the distribution of water is low.

In the border check method, parallel earth ridges guide the sheet of flowing water as it moves down the slope over the strips, which vary from 3 to 30 m in width and can be more than 100 m in length. A relatively large flow of water is needed. The land should have a uniform moderate slope parallel to the checks. Careful land preparation is necessary to ensure stability of the ground. The method is suited to medium textured, deep, permeable soils. On sandy soils, infiltration would be excessive unless the strips are short. Slow percolation renders it unsuitable for heavy soils. A drainage ditch should be sited at the end of the strip to carry away any excess water. Design involves achieving an optimum balance between soil type; slope, width, and length of strips; and water flow so that the desired depth of water will be applied uniformly to the compartment without excessive percolation at the input end. In agroforestry applications, it could be ideal because the trees could be grown along the check, the width of which could be sufficient for one or two rows of trees.

Basin irrigation is a simple, easily controlled system in which the field or compartment is divided into small units each of which has a level surface. The basins are filled with water which is all allowed to infiltrate, any excess being drained off. When leaching salts from the soil, the depth of water can be maintained for considerable periods by allowing continuous flow into the basins. The method is commonly used for this purpose, e.g., in saline forest plantation areas of the Indus Valley, the

basins being square and up to about 0.25 ha. It is favoured for small, close spaced, high-yielding plantations on heavy soils in Niger and Sénégal (see chapter 3). The method entails relatively high labour inputs.

In furrow irrigation, water is carried in channels down or across the slope of the field so that it seeps into the bottoms and sides of the furrows to provide the required wetting of the soil. The trees are planted on the sides or near the lips of the furrows. Careful grading of both land and furrows is vital for proper control and uniformity of application of water. Furrow irrigation does not wet the entire soil surface, irrigation depends on lateral movement of the water from the furrows. The method requires relatively high labour inputs and a high degree of skill and experience in directing water from supply channels into the furrows and controlling its flow. A disadvantage of the system is that tree roots tend to develop linearly along the furrow: trees tend to lean across the furrows and windthrow sometimes occurs later in the rotation. Unevenness of furrow levels and distribution of water can develop when soil conditions are not uniform. Regular maintenance of the furrows is important.

Furrow irrigation is frequently regarded as the most suitable for forest plantations, particularly when topography is uniform, slopes are not too steep, and the soil not too porous. The wide ridges and shallow depressions (at about 3 m centres) used in the Gezira and Khartoum Greenbelt irrigated plantations (see chapter 3) are an adaptation of the furrow system.

Corrugation irrigation is a system that combines water flow over the surface with furrow irrigation through the provision of parallel shallow furrows that are allowed to overflow. It has special applications in agriculture but is not applicable to forestry.

Water supply to gravity irrigation systems is effected either through open channels or pipelines. Open systems can be unlined or lined. Unlined channels are unsatisfactory because seepage losses are high, they encourage weed growth, and maintenance is costly. Turn-out devices can be permanent wood, metal, or concrete structures; portable siphons; tubes run through the bank; or temporary breaks dug in the bank, in that decreasing order of efficiency. The permanent devices often incorporate measuring arrangements.

The principal advantages of gravity systems are their relatively low investment costs if the land is initially reasonably level; that water is not required to be under pressure; and that labour costs can be low in some types, provided they are well designed and installed. The main disadvantages are that removal of the top soil in grading can impair fertility, often for years, and small flaws in design can have drastic consequences, e.g., high labour costs, soil erosion, and wastage of water. It is difficult or impossible to make small adjustments without affecting or disrupting the whole system (Bosshard 1966a; France 1969, 1977; Rawitz 1973b; Booher 1974).

Sprinkler Systems

Sprinkler systems are most applicable in areas of irregular topography where land grading is not feasible, in irregularly sloped areas, or where rapid application of relatively small quantities of water is desired. Applications to forestry are somewhat limited by crop height and costs but such systems are applicable in the early, establishment phase of forest plantation crops, e.g., the application at Mallam Fattori near Lake Chad, mentioned in chapter 3, and in agroforestry settings. The system was used in irrigation and irrigation–fertilization trials in sapling and pole-sized Douglas-

fir by the Weyerhauser Company in the Pacific Northwest of the USA in the late 1960s and early 1970s (Woodman 1971, 1973).

All sprinkler systems have, in common, a source of water under pressure, a system of pipelines to deliver water to the point of delivery, and nozzles through which the water is distributed.

Three types of distribution system may be recognized, the first being equipment with fixed distribution pipelines buried in the ground, the heads and risers sometimes also being permanently in place. They have the highest installation but the lowest operating costs and are the best adapted for perennial tree crops. Semipermanent distribution systems are similar to the fixed systems except that the laterals are portable, either singly or in entire sets. In fully portable distribution systems, all components including the pumps are portable. These types have the lowest installation but the highest operating costs.

There are three types of discharge devices: static sprinklers, nozzle lines, and rotating sprinklers. System design and selection of components, particularly the pump and mains components, involve technical considerations requiring specialist advice (Pillsbury 1968; Rawitz 1973a).

The advantages of sprinkler systems are that they are applicable to areas of irregular topography and shape without leveling; they can be used in areas of high water table or where there is a hard pan near the surface without increasing soil salinity; the amount and rate of water application are easily controlled so that runoff and deep percolation can be avoided, this gives them advantages in areas of high permeability. They can utilize a small, continuous supply of water better than gravity methods; water is distributed evenly if it is not too greatly affected by wind; they do not require land for water channels, ditches, and borders, thus saving land and the maintenance costs and inconveniences of open distribution systems. Operators can be trained easily and mistakes in design are usually less disastrous in their consequences than for gravity systems. However, the initial cost can greatly exceed that of gravity systems; water under pressure is required, with all that that implies for capital, maintenance, and operating costs and depreciation; water application can be affected by strong winds, resulting locally in deep percolation, losses by evaporation, and in wind drift and an aerosol effect; there are adverse effects on the foliage of some species, particularly if irrigation water has a high bicarbonate content and is applied when atmospheric humidity is low and evaporation from the leaves, therefore, rapid (Doneen 1972; Shmueli 1973; Arar 1975; Ayers and Westcot 1976).

Localized Systems

Localized irrigation systems, an umbrella term for trickle, drip, drop, or sip irrigation methods, are among those that cause wetting of only part of the soil, i.e., that at the base of and surrounding the root system of the plant. They are characterized by slow and low rates of application of water to the plant rooting zone through distribution pipes and orifices or nozzles organized either under or above the soil surface (Vermeiren and Jobling 1980).

The basic components include a pressurized supply of water, a control head, a main line with laterals, and distributors. To create the appropriate pressure in the water supply usually requires a pump and storage tanks or reservoir. The control head is usually sited at the highest point in the field and connected to the water supply to

regulate the pressure and amount of water provided, to filter the water before it enters the system, and, if required, to permit the addition of nutrients. The main line leads water to the submains, which supply the laterals on each side. These are fitted with distributors at predetermined points, i.e., opposite individual trees or groups of trees. From these distributors, water drips or oozes at a constant low discharge under pressure that varies slightly above and below atmospheric pressure along the line. The end of each submain and lateral can be opened to flush the system (Heller and Bresler 1973; Wood et al. 1975; Thomas et al. 1981; France nd; SETI nd).

The advantages of localized irrigation systems include the facts that, within limits, they can accommodate undulating ground, are relatively easy to manage, have relatively low labour costs, and are simple to operate. J. Gorse (World Bank, Washington, DC, USA, personal communication, 1984) stated that labourers became adept at installing and operating the system near Niamey in Niger (described in chapter 3). Other favourable aspects are economy in the use of water, ease of control of weeds and application of fertilizers, and enabling the soil moisture content in the wetted zone to be kept near field capacity, thus reducing the buildup of salinity there. Localized irrigation can be used successfully on excessively heavy or excessively light soils. In general, operating costs are low and the systems enable utilization of low-yielding water points such as springs and shallow wells. The principal problem of localized irrigation systems is the susceptibility of smaller pipes and the distributors to clogging by sand, silt, organic matter, algae, bacterial slimes, and precipitation of nutrients, colloidal materials, or lime. Root system size or spread and depth being a function of the volume of water applied at each irrigation, root development can be restricted through inadequate watering. Also, trees can die very rapidly if water is withheld for even a short period: thus the water supply must be reliable.

Localized irrigation has been used successfully in forest plantation development with saline water in desert conditions in Abu Dhabi (Wood et al. 1975); for windbreak plantings in the Great Plains and other dry areas of the United States (Thomas et al. 1981); and on the undulating ground of alluvial terraces beside the River Niger near Niamey and along the Sénégal River in Sénégal (Barbier and Louppe 1980; IBRD 1982; Hamel 1985; SETI nd; J. Gorse, World Bank, Washington DC, USA, personal communication, 1984). Use of the system has been under test in Pakistan (Sheikh and Masrur 1972). These developments give great hope for wider applications in areas where climatic conditions or water quality and quantity render the growing of trees virtually impossible, or of an additional option in more favourable areas. However, localized systems are by no means a universal panacea: each potential application must be very carefully analyzed before the apparent best alternative is selected (Heller and Bresler 1973; NAS 1974; Vermeiren and Jobling 1980).

Special Irrigation Systems and Devices

Because irrigation is practiced most in arid and semi-arid areas of the world, it is inevitably beset with problems arising out of the scarcity of water, which often has a high salt content, and soils that are, or under irrigation easily become, charged with excessive salts. Also, the more prevalent these features become the lower are the yields and the higher the costs. It is therefore inevitable that innovative methods are constantly being introduced. The introduction and development of various forms of localized irrigation systems, discussed in the previous section, is a good example of innovation to meet specific requirements. A number of other innovative methods and devices exists, many of them already or potentially applicable under particular conditions rather than generally, and not all of them are new.

Trials of variants of localized irrigation systems have included burying the fine ultimate distributors within the root zone of the tree. These efforts have usually failed with perennial crops because the distributors become clogged and cannot be cleaned without disturbing the plants. The same problems have negated trials with special types of distributors, e.g., spitters or bubblers (Pillsbury 1968; Rawitz 1973c).

Irrigation installations, including gravity systems, sometimes include arrangements for the reuse of water by collecting excess quantities that run off, and even seepage water that is collected in drainage ditches, returning it to the input end, and reapplying it to the crop. This practice entails the hazard that such recycled water can be unduly saline (NAS 1974). Similar hazards characterize the reuse of industrial and sewage water in many parts of the world, e.g., in Kuwait (Firmin 1971), near Melbourne (NAS 1974), in northern Victoria (Edgar and Stewart 1979), and in the Pacific Northwest of the USA (Alverson 1975). Purification of such wastewaters would be necessary if they contain materials toxic to plants or are unacceptable because they pollute the soil or groundwater. For this reason, wastewater from sugar factories is processed before use to irrigate *Eucalyptus* plantations in Sudan.

Several means of reducing water losses through evaporation, from either water or soil surfaces, are in use, albeit at present more in agriculture than in forestry. Their potential importance, particularly in areas where water is scarce may be gauged from the fact that 25–50% of the water applied to a crop by irrigation is lost by evaporation from the soil surface (IBRD 1979b). An important recent trend has been to convey water in pipes rather than open channels, particularly unlined ones that give rise to added losses from seepage, which has important implications in relation to waterlogging. Liquid chemicals, waxes, and plastic sheeting are sometimes used to cover the surface of water in open reservoirs. Plastic aprons about 1 m in diameter are sometimes used to reduce evaporation from the soil round the plant (Wood et al. 1975). These devices have the added advantages that they trap dew from the soil or rainwater from above, and direct them, if the apron has the correct slope, to the base of the tree.

Because about 99% of water absorbed by plant roots is released into the air from leaf surfaces, several methods are used to reduce transpiration water losses, e.g., destroying unwanted phreatophytes and other weeds along water channels or in the plantations, choosing or breeding plant types that transpire relatively small quantities of water, coating leaves with antitranspirants, and planting shelterbelts to reduce wind velocities.

An age-old practice for temporary watering of individual plants or groups of them, particularly during the first 1 or 2 years until their roots reach the groundwater, is pitcher irrigation (Goor and Barney 1968; NAS 1974). This method is one of several that is being tested and developed for afforestation in arid lands, e.g., in the Thal Desert in Pakistan (Khan and Sheikh 1983). A related method, used in Spain and elsewhere, is that of irrigating the root zones of planted trees by pouring water down tubes (e.g., hollow bamboo) inserted into the soil at an angle from the vertical (Goor and Barney 1968). A similar system is used in dry areas of South Australia where watering of each individual tree is done through a 60 × 15 cm perforated pipe (Johnson and Hall 1970).

Trees are often watered immediately after planting and for one or two seasons after that to assist them to develop until their root systems are in contact with permanent supplies of moisture in the lower horizons of the soil, after which they can fend for themselves. This system is most effective when both planting and subsequent watering are timed so that the plant can benefit to the maximum extent from the rainy

season, i.e., planting is done early in that season and watering is done so as to cover breaks in the rains and to extend the rainy season. Irrigation of trees in river flood basins in Mali, Niger, and Sénégal is often done for only one or two seasons after planting to enable the tree roots to reach shallow water tables. It was used in this way for the establishment of fast-growing *Eucalyptus* plantations at Mallam Fattori in Nigeria (see chapter 3). Light watering can be harmful if it results in the development of a shallow root system; it should be sufficient in both amount and frequency to ensure an adequate depth of moistened soil and hence of root development. Plantations of *Pinus eldarica* near Teheran in Iran suffered heavy windthrow because irrigation impeded deep root development. Temporary irrigation by hand from water bowsers is widely practiced, for example, in and on the slopes into the Indus Plain in Pakistan.

Subirrigation is a method that is unlikely to be of much interest in field forestry. It can be applied only in areas where a very permeable soil, e.g., peat, is underlain by an impermeable layer and by a high water table. The root zone is wetted by artificially raising the water table at appropriate intervals. The method is flawed, however, because irrigation is normally practiced in dry areas where the groundwater invariably contains at least some dissolved salts. These are brought up to the root zone by the raised water and remain there when the water is evaporated or transpired by the plants. In this respect, subirrigation has two major built-in drawbacks: first, shallow groundwater usually has the highest salt content and, second, the whole situation precludes any possibility of leaching out accumulated salts. Two large agricultural areas of organic

Tunisia: A concrete-lined furrow from which water is diverted as needed to unlined furrows adjacent to the rows of poplar on each side.

soil that were once irrigated in this manner are the Sacramento River delta in northern California and the Huleh Valley in northern Israel: they are now irrigated by sprinkling (Pillsbury 1968; Rawitz 1973c).

Another method of reducing water use that is of limited application in forestry, except perhaps the nursery phase, is to restrict deep percolation by underground moisture barriers of asphalt, plastic sheeting, or layers of compost or manure rich in colloids. Placing the barrier in position involves the removal of the soil down to the depth at which the sheet is to be placed and then replacing the top soil. The barrier is placed about 60 cm below the surface with gaps at intervals for drainage (Mendizabal and Verdejo 1968; NAS 1974; France nd).

Rainwater Harvesting: Runoff Farming

Rainwater harvesting as a means to provide water seasonally or, with storage, over longer periods has been used in arid areas for thousands of years to grow agricultural crops and trees for fruit, amenity, and other purposes. The approach results in variable success because, being dependent on rainfall, it is not reliable. It is potentially more useful in areas that have a Mediterranean climate. Excavations in the Negev of Israel and Jordan have revealed the complex systems formerly used; the Romans used such systems, in conjunction with underground water storage cisterns, in North Africa until they were largely destroyed by the Banu Hilal invaders in the 11th century A.D.

In one form or another, rainwater harvesting is still used, e.g., in Afghanistan, Australia, Botswana, Burkina Faso, India, Iran, Israel, Mexico, Niger, the Thal Desert in Pakistan, and Kassala Province of the Sudan, often in areas with rainfall as low as 25–80 mm. The water is either fed directly to trees or stored for use later. Basic components of the system consist of land-surface alteration so as to channel water into predetermined areas and modification of the soil surface to maximize runoff. The configuration of the land surface is changed by the construction of ponds, ditches, walls, or soil ridges on contours, or microcatchments.

Means of improving the runoff capacity of the soil may be physical, e.g., by removal of rocks and vegetation or compacting the surface, or both; chemical, e.g., using sodium salts, silicones, latex, asphalt, or wax; or by using waterproof covers such as plastic, rubber, or light metal. The methods used are usually site specific: they are geared to the local soil, topographic, and climatic conditions. Limitations are that the systems are rainfall dependent, the materials used deteriorate due to weathering and need careful maintenance or replacement, and there can be side effects such as soil erosion (Badi 1967; NAS 1974; Evenari et al. 1975; Ovrut and Ovrut 1977; Mehdizadeh et al. 1978; Walker 1979a, b; M.I. Sheikh, Pakistan Forest Institute, Peshawar, Pakistan, personal communication, 1984).

A system of water trapping is used to irrigate individual fruit trees in the dry region of northwestern Mexico. A square plastic sheet about 2.5 × 2.5 m is placed round the base of each tree and weighed down by stones. The ground is bare and formed so that its smoothed surface slopes from all directions to the base of the tree. The plastic sheet captures and feeds to the tree not only the precipitation that falls on it but also the dew that is regularly trapped on its lower surface at night (C. Palmberg, Forest Resources Division, FAO, Rome, Italy, personal communication, 1983).

Criteria for Selection of Irrigation Systems

It is frequently stated that there is seldom, if ever, a ready-made irrigation practice available to fit any specific set of circumstances. Each case requires thorough, realistic appraisal of the factors that apply before a selection is made of the system that would result in the best sustainable economic return. Although one or two criteria might weigh more heavily than the others, the selection would be made after analyzing all relevant features of the case. The principal criteria to be considered are reviewed in this section. The time scales involved in irrigated forestry render it especially important to make the correct choices because changes, if indeed they can be made without disrupting the crop, would usually be costly.

It is one thing for selection of a system to be made for a pure forestry plantation application but quite another where forestry is to be integrated with irrigated agriculture. In the latter case, unless the forester can be involved at the beginning and so influence the selection of the system to be applied to both crop categories, he/she may be faced with the problem of how to make the best of an existing situation that is possibly not ideal for the perennial tree crop. In that case, the tree crop would have to be tailored, i.e., its design and the species selected to fit the preexisting irrigation system.

Of the criteria that bear directly on the cost and operation of a system, the first to be considered would usually be the land. The costs of land grading are high. If slopes are steep or undulations marked, earth work could result in some of the trees being grown in infertile subsoil. In such cases, gravity systems would probably be inappropriate, particularly if the shape of the area is sufficiently irregular to complicate arrangements for the movement of water. If the terrain and soil conditions are such that irrigation might cause erosion, then sprinkler or localized systems might be applicable because they can be used with minimal land grading.

Soil characteristics have an important bearing on the selection of an irrigation system. Thus sprinkler and localized systems with their characteristics of ease of regulation and control of water application are more suitable than gravity systems where soils are light or shallow, excessive percolation or erosion can occur, soil texture changes are frequent, soil salinity is high, a shallow calcareous pan occurs, or the water table is high. On the other hand, gravity systems, particularly the basin method, are more appropriate in fine, slowly permeable soils and where saline or alkaline conditions require leaching to be done.

A relatively large number of considerations regarding water will influence the choice of system. Water is always costly and often scarce, so that, other factors permitting, systems such as localized or sprinkler systems are often preferable to gravity irrigation in which water distribution can be complex and difficult. Sprinkler systems enable rapid applications of small quantities of water and, properly operated, they can be economical in the use of water even if winds are moderately strong. Both sprinkler and localized systems can utilize a small, continuous supply of water more effectively than gravity methods, which require large, intermittent water discharges. It is generally recognized that methods permitting close control and uniformity of application and downward movement of water into the soil facilitate salinity control. This is a consideration in favour of sprinkler and localized systems. Among gravity systems, furrow irrigation is the most difficult under which to correct soil salinity.

When irrigation water itself is saline, the capability to apply slowly and uniformly the small amounts of water required to maintain water tension in the root zone makes the localized system preferable to all others. Sprinklers are less desirable because the water-borne salts can damage foliage. That sprinkler systems require water to be supplied under pressure can also be a disadvantage because this entails not only pumping costs but also installation and maintenance costs that are not characteristic of other methods.

Because irrigated crops are sensitive to interruption of watering schedules, it is essential for the water supply to be reliable. This applies particularly to localized systems where the root system is usually less extensive than when other methods are used, so that withdrawal of watering can lead very quickly to death of the trees.

In efficiently operated irrigation, there is little difference between systems in respect of their effect on water use or loss through evapotranspiration, the effect of wind on sprinklers not withstanding (Doorenbos and Pruitt 1977). Doneen (1972) compared various systems with respect to their irrigation efficiency, i.e., the relationship between the amount of water calculated as being required to raise soil moisture to field capacity and the amount actually applied, in effect a measure of the degree of irrigation control. He gave the following general guide: basin irrigation, 60–80%; border irrigation, 40–75%; furrow irrigation, 55–70%; contour-ditch irrigation, 50–55%; and sprinklers, 65–85%. These data indicate that sprinklers and basin irrigation are the easiest to control.

When biological criteria are considered, it is clear that furrow irrigation has the disadvantage that root systems are distorted by being aligned with the axis of the furrow. This is particularly so when, as is usually the case, the trees are planted on the side of or close to the furrow. The feature leads to leaning of the trees and windthrow. Restriction of root systems can be an unavoidable, built-in disadvantage of localized irrigation. However, this defect can be minimized by applying sufficient water (if it is available) to extend the root zone of the plant to reasonable dimensions.

Ease of management, simplicity of control, moderateness of labour and maintenance costs, and the readiness with which labour can be trained to maintain and operate a system are often claimed as advantages for sprinkler and localized systems. These generalizations may be valid but much would depend on the detailed conditions, traditions, attitudes, and motivations that apply in each specific instance. When choices among systems are to be made, a comparison based on a technical, financial, and economic analysis of each feasible alternative is the only safe course to follow. In general, it is characteristic of gravity systems that small flaws in design or installation can have drastic consequences, their correction involving serious disruption and high costs. The long time scales of forestry irrigation schemes have major implications for the choice of system, i.e., the need for them to be sustainable and permanent.

6. Assessment of Needs and Potentialities

Population and Socioeconomic Trends

The implications of increasing populations and their demands for wood and tree products, particularly in arid and semi-arid areas, are discussed in chapter 2.

The outline by Glesinger (1960), supported by those of Thirgood (1981) and Meiggs (1982), of the deterioration of the Mediterranean basin over a period of 2000 years or more provides a good example of what can happen if population growth and accompanying trends in natural resource and land use such as those that have taken place during this century continue. He explained how enhanced but incautious production to meet the rising demands of an increased, progressively more sophisticated society led in time to widespread degradation of the landscape, undermined the basic resources of the region, and destroyed their capacity for production. This led in turn to the decline of cities and peoples and was one of the causes of the spread of desert conditions over about half a billion hectares of land. This process has not yet halted, although some enlightened development, e.g., well conceived irrigation schemes in some North African countries (partly the outcome of the FAO regional project that Glesinger was promoting) give hope for the future. Barbier (1978) and Barbier and Louppe (1980) describe the impact of increases in human population and domestic stock on the natural forest resources of the Niger Valley and disruption of the productive capacity of the landscape. They emphasize the particularly deleterious effects of urban concentrations of people in expanding islands of depletion and desertification. Other examples of such trends occur in Mali and Sénégal (see chapter 3).

It may be expected that increases and distributional changes in population will continue, with no discrimination in the arid or any other zones, in their associated threats to the well-being of land and water as the basic resources for production of food and wood. Strategies to meet society's needs for these commodities and to ameliorate the effects of demands on the land, water, forest, and other resources will entail inputs by specialists in several disciplines, including economists and sociologists, agriculturists and foresters. It may be expected that they would collectively identify priority needs, including those for wood and other tree products, and feasible opportunities to meet them from various forms of high-yielding forest plantations, including irrigated plantations.

Need for Tree Products

The nature of products and values sought from trees and forests, including those grown under irrigation, varies widely. In the so-called Western world, the major need is usually for industrial wood for the production of reconstituted wood and pulp

products, wood for general and construction purposes, and some high quality, fine woods. In general, the quantities of wood used as energy sources are small. However, in less-developed countries, including many in the arid and semi-arid regions, this pattern is virtually reversed. Wood as a primary domestic energy source tends to transcend all other forms, with wood (often in the form of poles) for building as the next most important. In these regions, trees are also important sources of fodder for browsing animals or tethered and stall-fed stock. They are used as sources of oils, pharmaceuticals, traditional medicines, tanin and other bark products such as fibre, honey, fruit, thatching materials, and food for silk worms. Beneficial environmental influences such as shade and shelter and the ameliorative effects of windbreaks and shelterbelts in reducing wind velocities and thus evaporation and movement of sand are widely sought after through tree plantation. In some arid-zone countries, such as those with high oil revenues, e.g., Kuwait, Abu Dhabi, and Saudi Arabia, amenity values, shelter for wildlife, and the like are sometimes the most important objectives sought from irrigated tree-planting schemes (Firmin 1971; Arar 1975; Wood et al. 1975; Satchell 1978; Wood and Synott 1978).

It should not be overlooked that growing of tree products frequently results in the provision of habitats for undesirable forms of wildlife, e.g., grain-eating birds, wild boar, and insects.

For countries where wood is an important source of domestic energy, total average rates of consumption are normally expressed in terms of cubic metres per person per year. These vary according to the extent to which alternatives such as kerosene or agricultural residues are used as fuel. World Bank reports give estimates varying in the range 0.5–1.2 m^3 ha per year. A small proportion of this (often about 10%) is used as poles and much of the remainder is converted to charcoal. The demand and search for wood to be used as domestic fuel, and browse, are important factors in the development of depletion zones and desertification round towns, cities, and concentrations of rural populations already referred to earlier in this chapter.

In an arid environment, irrigated plantations can supply fuelwood and other products that must, otherwise, be transported over considerable distances: Bringing light fuels to a village in Egypt.

The important need for deliberate measures to produce wood, primarily fuelwood, to meet the needs of large concentrations of population in arid areas may be illustrated by reference to three cases in which it is proposed that the demand might be met through large-scale irrigated plantations.

The first is Pakistan where 30% of all imports consist of fuel oil and the needs of the future are said to make the development of fuelwood plantations essential (M.I. Sheikh, Pakistan Forest Institute, Peshawar, Pakistan, personal communication, 1985).

The second concerns the needs of the burgeoning city of Niamey in Niger. Production from the natural open woodland in the vicinity is of the order of 0.5 m^3/ha per year at best, and has declined to virtually nothing as a result of unrelenting intensive harvesting. A start has been made to develop feasible means of producing wood under irrigation (see chapter 3). Barbier (1978) stated that 30 000–35 000 ha of plantations would be required to meet the demand fully. At this stage, a development on this scale appears to be impractical. A solution largely based on the use of alternative fuels is being considered but the favoured approach to tree growing under irrigation is currently to integrate it with agriculture.

The third case is that of the Gezira area discussed by Foggie (1967). The population here was 1.2 million in 1956 and 1.9 million in 1966 and was forecast to increase to 2.6 million in 1981. At 0.9 m^3/person per year, the wood requirements of these people amounted to 1.5 million m^3/year and would become 2.4 million m^3 in 1981. Only 3% of the 1.5 million m^3 used in the Gezira in 1966 was met from internal production. The remainder came from remnants of the former natural woodland in the area, growing at perhaps 0.5–0.6 m^3/ha per year, and the great bulk from an expanding arc of clearance of indigenous open savanna lands for agricultural production, an average of 270 km away. Meantime, the average rate of production of the irrigated plantations, at 6.6 m^3/ha per year, was about half the potential average. Expansions of the irrigated plantation program were in progress and others were planned. This was considered to be sensible because the Gezira and other irrigation schemes nearby were being looked to as sources of supply for the large populations of several growing cities in the region. The balance of wood required to meet these needs was simply not in sight. Compared with Foggie's perception of future needs, the expansion of irrigated plantations has been negligible.

Although there is a potential for a proportion of the needs in these cases to be met through agroforestry, including large-scale shelterbelt development, there could be instances in which large-scale irrigated plantation developments would be warranted in spite of the development costs and the demand for land for agriculture. One of the benefits of such development would be that the pressure on the remaining indigenous woodland would be reduced, making it possible for the regional desertification problems to be tackled more effectively.

Land and Water for Wood Production

A shortage of water exists not only in the arid regions of the world but also in many humid climate areas. This arises because water requirements for agriculture and industry exceed natural supplies. Even in Europe, according to Gindel (1973), there is increased anxiety over the state of water reserves and shortages are forecast if industry continues to expand. During the second and third quarters of this century, water use in the United States increased at twice the rate of population growth and shortages continue to appear throughout the country.

Efforts to ensure rational apportionment of scarce water for use by the people and for their agriculture and stock were described by James (1973) for northeastern Nigeria, as between agriculture and forestry in the Thal Desert area of Pakistan by Khan (1960b), and by Schechter (1977) for Israel. Municipal and industrial effluents are used increasingly for irrigated agriculture and, to a lesser extent, forest production in the United States where the availability of water for such purposes is regarded as an important opportunity (Alverson 1975; Urie 1975). Very large demands for water for irrigation developments to meet the demands of growing populations have been made in many parts of the world in recent decades, in areas as far apart as Australia, China, Russia, and North and South America.

The allocation of land and water for irrigated timber production, particularly where these two basic commodities are scarce, brings this form of production into conflict with agricultural production. Thus, in the Indus Valley in Pakistan, agriculturists sometimes resent the use of land for state forest plantations, particularly if they are not obviously highly productive of wood. Kanschik (1961) suggested that, when available land and water are required for agriculture, the best course is often to integrate irrigated forestry with agriculture. Such a strategy would be reinforced by the rationale that underlies Swaminathan's contention (1980) that, where forestry becomes a people's movement rather than that of a state forestry department, the basic requirements for timber production are better assured. In the Indus Valley of Pakistan, farmers unable to secure land with irrigation water rights in agricultural areas are often eager to enter into agreements with provincial forest services to participate in irrigated agroforestry activities on land controlled by the latter. However, the fact that agroforestry would not necessarily solve the problems of enormous deficits of wood to meet basic needs of large population concentrations is illustrated by the cases discussed earlier in this chapter and those at N'Debougou in Mali (IDRC 1981) and around Mopti in Mali where heavy demands for fuelwood for a relatively recently established smoked-fish industry have seriously depleted local wood supplies (M. Grut, World Bank, Washington, DC, USA, personal communication, 1984). In every case, however, whether production is to be of wood and food or wood alone, careful analysis of competing needs and consideration of all feasible alternatives is necessary (Glesinger 1960).

It has been noted that land for irrigated forestry crops often takes the form of small, scattered areas not used for agriculture, such as strips along boundaries, roads, and canals and residual areas of irregular shape and microrelief. Such cases are cited for Zimbabwe (Barrett and Woodvine 1971), Mali (IDRC 1981), Niger (Barbier 1978; IBRD 1982; Hamel 1985; J. Gorse, World Bank, Washington, DC, USA, personal communication, 1984), and Sudan (Foggie 1967; Jackson 1976; Ali 1979). Useful production can result from use of such areas but some of these authors point out that, in total, they might in aggregate be too small to produce the required quantities of wood. Also, spare areas of this sort, as in parts of the Gezira, are simply dumping grounds for used irrigation water and often become waterlogged and therefore useless. According to an FAO-sponsored group that visited the USSR, unused land within irrigated agricultural areas there is often put under tree plantations with the twofold object of producing wood and lowering the water table through transpiration. The possibility should not be overlooked, as stated by Pryor (1953) in relation to some areas in the Euphrates Valley in Iraq, and by Veltkamp (nd), that tree plantations can often be economically more attractive than agricultural cropping on marginal lands or those that have been worked out.

It is axiomatic that conflicts between competing alternatives for use of land diminishes with declining quality of the tracts. Thus Firmin (1971), Wood et al. (1975), and Busby (1979) did not mention any difficulty in securing more or less saline desert areas for amenity plantations in Kuwait, Abu Dhabi, and Iraq.

The conclusion to be drawn from the viewpoints expressed in the literature is that beneficial use can certainly be made of some areas of the kinds mentioned. However, their true characteristics must be realistically assessed before scarce development resources are committed to them. If they are affected by salinity, they should be recognized and treated accordingly (Khan 1966). Also, the forestry case for additional or better land and more water must be clearly made if that allocated is not adequate to meet the production objectives set.

Opportunities frequently occur, as in the Sudan (see chapter 3) for the use of industrial, municipal, and irrigation wastewater for the irrigation of relatively extensive block plantations. Such effluents often contain levels of salts and minerals that, in the absence of treatment, can in time cause public-health hazards or put land out of production (Laurie 1974; Alverson 1975; Urie 1975; Edgar and Stewart 1979).

There is much accumulated experience of poor production or disasters that result from irregular or inadequate water supplies. Forest plantations at or near the ends of lateral water supply lines in the Indus Valley are frequently without water or, at best, served with insufficient quantities because of breakdowns or design inadequacies in the supply systems. Also, indicated rates of supply are not always achieved in practice (Lerche and Khan 1967). Use of water from the Nile for irrigation at Gezira and for part of the Khartoum Greenbelt plantations[1] is interrupted each year from mid-March to mid-August by the provisions of the Nile Waters Agreement between the Sudan and Egypt. This has a considerable impact on irrigation schedules and, according to Bayoumi (1976), some 35% of the land available for irrigation was not used for this reason. However, as Masson and Osman (1963) and Khan (1966) stressed, it is important to know with certainty what quantities of water will be available, and when, so that irrigation schedules can be planned and implemented accordingly. Unexpected interruptions of water supply, particularly if they are prolonged, can have catastrophic effects. The disaster, described in chapter 3, that overtook the half of the Khartoum Greenbelt plantations that is dependent on the Gezira scheme canal is a case in point. Over-supply can be equally undesirable, as is the case when water surplus to irrigated agricultural requirements is dumped into forestry areas (Bosshard 1966e; Foggie 1967; Laurie 1974; Jackson 1976; Ali 1979).

The need for economy in the use of water has been stressed by several authors. Khan (1966) and Schechter (1977) stated that, because water is a scarce commodity, its efficient use should be regarded by the user as an obligation. Irrigationists stress that an important strategy for the use of scarce water is to practice opportunity or multipurpose use of it, e.g., by using drainage, tail, or other forms of secondary water for plantation irrigation. Gindel (1973) suggested that, because plants with a high rate of transpiration can endanger water resources in some circumstances, their use should not be encouraged. Trees sometimes need water only for long enough to get their roots down to permanent water and those that need permanent irrigation usually need less in the early stages of development than they do later. Irrigation schedules should be compiled accordingly (Pryor 1970; Jackson 1976). Reference has already been made to

[1] The other half of the Khartoum Greenbelt plantations is unaffected by this factor because it is irrigated with sewage effluent from the city.

the important water-conservation benefits to agricultural production and in other ways that result from the development of shelterbelt systems in crop lands (see, among others, Bayoumi 1976, 1977; Saleem 1973, 1975; Thomas et al. 1981).

The use of water for forest plantation irrigation does not always raise conflicts due to agricultural needs. Barbier (1978) describes certain bottomlands along the Niger that are subject to seasonal flooding and to lateral seepage, factors that together sustain the growth of the plantations. In the same area, pumping water out of the Niger for dry-season irrigation of forest plantations does not interfere with agricultural irrigation because the Niger, in the vicinity of Niamey, floods during the dry season when agricultural water demands peak, yet there is more than enough for both (IBRD 1978; Barbier and Louppe 1980). J. Gorse (World Bank, Washington, DC, USA, personal communication, 1984) contends, on the basis of recent experience in Niger, that irrigation of trees should not be undertaken unless the water is free or nearly so: pumping it from a river is very costly.

The special case has been noted of irrigation of tree crops when only saline water from boreholes and hand-dug wells is available, necessitating the use of methods of application that minimize the effects of the salts on the plant. Those used in Tunisia and other parts of North Africa have been described by Van Hoorn et al. (1968) and Arar (1975); in Abu Dhabi by Wood et al. (1975), Satchell (1978), and Hallsworth (1981); and those in Kuwait by Firmin (1968) and Wood and Synott (1978).

Technical Feasibility

Water for irrigation

Quality

Irrigation water always contains impurities in the form of dissolved or suspended materials, the amount and nature of which determine the usefulness of the water for the purpose. Good indicators of water quality are its content of dissolved salts, the amount of suspended solids, and the content of pollutants from human sources. Dissolved salts may affect plant growth and soil properties; agrochemical residues may affect the biological equilibrium of the soil. Suspended matter, although it accounts partly for the high production of some irrigated soils, such as those in the Nile Valley, can also adversely affect water supply and distribution arrangements and mechanisms. It is thus important to know the characteristics of the water, and the individual and combined effects of substances in it, in relation to these factors (Yaron 1973).

Water quality evaluation is normally undertaken for irrigated agriculture on the basis of problems that can be induced by poor water quality. Four categories of such problems are recognized in guidelines given by Ayers and Westcot (1976): salinity, which affects crop water availability; permeability, which affects the rate of infiltration of water into the soil; specific ion toxicity, which affects sensitive crops; and miscellaneous factors that affect susceptible crops. Because water quality can be affected simultaneously by more than one of these types of problem, evaluation is done for each category separately, in relation, in each case, to consideration of the level of salts likely to cause problems; the mechanisms of soil–water–plant interactions likely to be affected sufficiently that there is loss of production; the probable severity to which the problem would build up after long-term use of the water concerned; and the management alternatives available to correct or minimize the problem.

Excessive soil salinity, particularly in the upper horizons from which most plants take the bulk of their water and dissolved nutrients, renders it more difficult for water to be taken up by the roots. The objective of management alternatives to overcome salinity problems is, therefore, to improve soil-water availability to the crop. Some of the alternatives are to irrigate more frequently (although not to the extent of inducing or exacerbating other soil-water problems), using tolerant species or varieties, routinely using additional water for leaching, changing cultural practices (e.g., using appropriate fertilizers), and changing the method of irrigation to one giving better salt control. More drastic actions would include changing the water supply and establishing artificial drainage (if none existed before) if there are water-table problems.

A number of examples have been documented of measures to permit the use of saline water. In arid areas in Tunisia, where there has been a large increase in recent years in the area under irrigation, trees have been grown successfully with water containing up to 5 g of oven-dry salt material per litre, and with water that is also gypseous. Success in this work has depended on frequent applications of small quantities of water to reduce soil-water tension, correct drainage, and periodic leaching, taking into account that effected by winter rainfall (Cointepas 1968; Van Hoorn et al. 1968; Arar 1975).

Successful plantation work was done in desert areas of Abu Dhabi in spite of the use of borehole water containing 2500–16 000 ppm of salts. *Casuarina glauca* and *Eucalyptus camaldulensis* grew an average of 1.7 m/year in height over the first 7 years (Wood et al. 1975; Hallsworth 1981).

Reduced permeability may be caused by many factors, particularly those of water quality. High sodium content in the water breaks down soil structure causing finer soil particles to disperse and fill soil-pore spaces and thus to seal the soil surface. Water with low salinity is corrosive and depletes the upper horizons of the soil of readily soluble minerals and salts, e.g., those of calcium, with similar effects to those of high sodium water. Management alternatives are to irrigate more frequently, use deep cultivation and tillage (which is not usually feasible once a tree crop has been established), increase the time allotted for a given amount of irrigation, collect and recirculate runoff water, match application rates to those of infiltration when sprinklers are used, and apply organic residues to the soil.

Specific ion toxicity is caused by sodium and chloride ions, to which many tree species are sensitive. Management options to minimize or correct such problems are to irrigate more frequently, to increase the quantity of water used for leaching, and, in the case of sodium toxicity, to use an amendment such as gypsum, as is done in the Indus Valley of Pakistan (Shah Mohammad 1978), or sulphuric acid.

Some crops are sensitive to excess nitrate or ammonium nitrogen. Although abnormal soil pH is often cited as a problem, it is not of itself a true problem but rather an indicator of one. Management alternatives in these situations are to plant crops that are not sensitive, to blend or change the water supply, to change the irrigation method, or to apply sulphur or gypsum to soils of high pH or lime to those of low pH.

Species trials were undertaken in Kuwait with water containing 4000–5000 ppm of salts. Care was taken when irrigating to maintain permanently moist conditions in the root zone. Species were screened in relation to various concentrations of boron, zinc, bicarbonate, and ratios of magnesium to calcium, sodium to calcium, sodium to potassium, and sodium to calcium plus magnesium. (The results are given in appendix 2, Table 10.) It was found that *Prosopis* could be grown in the seawater of that Gulf

region provided that the sodium in the water could be replaced with potassium (Firmin 1968). Arar (1975) cited a case in which problems were caused in irrigated plantations by excessive nitrogen content of the water.

Where sewage effluent is used for tree plantations, e.g., trials in Kuwait (Firmin 1971), in northern Victoria (Edgar and Stewart 1979), and in the United States (Urie 1975), there are important possible long-term implications in using such water because it contains high levels of ions and other materials that could build up in the soil and become harmful to plant growth and pollute groundwater. The need for careful monitoring and assessments in such practice is stressed by Ayers and Westcot (1976).

Quantity

Predicting the water requirements for irrigating a crop is complex because it must account for a large number of often highly variable interacting factors. The highly theoretical, scientifically based methods that are described in the literature have been developed in relation to agricultural crops, most of which are annual, with extrapolations to perennials. Relatively little comparable work has been done in relation to irrigated tree crops, practice for which seems to be based at least as much on trial and error or on the experience and judgment — even hunches — of individual practitioners as on scientific experimentation (Raeder-Riotzsch 1965).

The empirical approach to assessing crop water requirements is probably the most valuable to use in practice because theoretical approaches usually do not answer questions that relate to actual water availability in the field — such as how much water trees really need, when and for how long it is needed, and how long a tree can tolerate no irrigation and at what times of the year. It is important to distinguish between the water requirements of a tree crop for good growth and potential water consumption, i.e., the amount that would be used if it were available in more or less unlimited quantities but that would not give meaningful increases in growth rates. It seems relevant to bear in mind that, in many dry areas of the world, farmers find ways of growing satisfactory crops on applications of as low as 500 mm of water. Foresters are accustomed to using two or three times this quantity; it is not usually established that such rates are warranted.

In Pakistan, water allocations for irrigation of forestry crops in the Indus Plain have for many years been granted on the basis of 70 (sometimes 100) cusecs[2] per 100 acres. The former figure is equivalent to about 1.46 m/ha per year or 1460 mm of rainfall. This is a little more than the foresters usually aim to apply in practice, as indicated in Table 4.

From trials at Khanewal in Punjab, Sheikh (1974a) concluded that irrigation at 91–122 cm/year is sufficient for optimum growth of *Dalbergia sissoo* after the second thinning at the 10th year. The results of other research to establish watering rates in Pakistan are discussed in chapter 3.

At Gezira, Khan (1966a) undertook trials that indicated that, in the Sudan, *Eucalyptus microtheca* requires applications of water at 2-week intervals from July to December and at 6-week ones from January to March, the total application being 124 cm/year. Work by Ahmed (nd) confirmed this regime. For *E. camaldulensis* trials on river terraces in Niger, Delwaulle (1979) found that there was little difference in growth of 2-year-old trees between those given total applications of 270 and 460

[2] Cusec is a volumetric unit of flow equal to 1 cubic foot per second past a given point.

Table 4. Average annual requirements of water by various annual and perennial crops.

Crop	Water requirement (cm)
Wheat	33
Cotton	
Desi	46
American	63
Maize (= corn)	63
Rice	162
Sugarcane	140
Forest plantations	137

Source: Lerche and Khan (1967)

cm/year and Barbier (1978) reported a similar result for rates of 250 and 500 cm year. In each case, both rates resulted in considerably more growth than no irrigation.

Trials with two poplar clones on a sandy loam to loamy soil in Israel indicated that the best irrigation regime would be to water at 2-week intervals (when soil moisture would be at about two-thirds of field capacity) at an overall annual rate of 135 cm, as an addition to the 60 cm of annual rainfall characteristics of the area. These trials illustrate the type of empirical work that is required to establish optimum irrigation rates in specific areas with particular species.

Several workers contend that tree crops require more water for optimum growth than do agricultural crops. This may be due to some extent to the perennial nature of tree crops. Goor and Barney (1968) stated that trees require twice the amount of water that agricultural crops do, but, for the specific conditions with which they were concerned, Foggie (1967) suggested 3.5 times and Edgar and Stewart (1979) 2.2 times more.

In deciding when to irrigate, research is required to establish plant response to soil-moisture depletion patterns and growth in relation to various soil-moisture treatments. These relationships provide the information necessary to determine the optimal irrigation requirement, timing of irrigation, amount of each application of water, irrigation efficiency, and seasonal water use.

Several plant water-status indicators can be used as a guide to irrigation requirements by specialists developing irrigation schedules, e.g., darkening of leaf colour in some species as moisture stress begins to affect the plant, curling or changes of angle of leaves, reduced rate of elongation by the growing shoot, slowing of stem diameter growth, and reduction in stomatal aperture. Soil-water potential is measured with instruments such as tensiometers and neutron probes.

Doorenbos and Pruitt (1977) explain that prediction methods for crop water requirements are used because of the difficulty of obtaining accurate field measurements on which to base them. They present detailed guidelines for the calculation of water requirements of crops under various climatic and cultural conditions to give information needed for project planning. Their guidelines also provide a useful starting point for research on crop water requirements. They define crop water requirements as the depth of water needed to meet the water loss through evapotranspiration (*ET crop*) of a disease-free crop growing in large fields under soil water, fertility, and other conditions that permit it to achieve its full production potential in the given growing environment.

A three-stage procedure is recommended for calculating *ET crop*: first, calculation of the effect of climate on crop water requirements; second, calculation of the effect of the specific crop characteristics on crop water requirements; and, third, calculation of the effect of local conditions and cultural practices on crop water requirements. The procedures for these calculations are explained in detail, with examples and with computer programs for calculation (Doorenbos and Pruitt 1977).

Tree species for irrigation

The range of environments in which trees are grown under irrigation, and the objectives for which they are grown, are as diverse as the plantation sites are widespread. Accordingly, the number of species that have been found to be suitable under specific conditions and for specific purposes is very large; anything approaching a comprehensive listing here is neither possible nor appropriate. The purpose of this section is to review the principal criteria for selection or rejection of species, the need for further species testing and selection, and general approaches to this. Reference is made to species included in appendices 1–4, which were compiled from the literature on irrigation of forest trees reviewed. They comprise four separate lists:

- A list of some of the principal species used showing, by countries, published information on growth rates under irrigation (appendix 1);
- A list compiled by Firmin (1968), on the basis of trials in Kuwait, indicating his ranking of the species for tolerance of various expressions of salinity (appendix 2);
- The lists given by Boyko and Boyko (1968) of species that performed either well or moderately well in irrigated trials under desert conditions at Eilat in Israel (appendix 3); and
- The ranking by Bosshard (1966c) of species tested in the Khartoum Greenbelt in the Sudan as to their tolerance of interruption of irrigation for different lengths of time (appendix 4).

The last three lists are as given by the authors cited. The compilation in the first list reflects principally published volume growth rates. Its primary purpose, like that of including the other three, is to provide a point of entry into the important aspect of species selection that might be of value to irrigation foresters involved in planning and conducting forest irrigation schemes in their own particular spheres.

Criteria for selection of species will vary according to the objectives and conditions that apply in each case. Species would usually be chosen that are adapted to the environment and the silvicultural system to be applied at the plantation site, and that have water requirements that can be met with the water available (Ali 1962). As an indication of the care that should be exercised in species selection, it may be noted that *D. sissoo* for example, is a deciduous species that thrives best where there is an effective annual dormant season, as in the northern parts of the Indus Valley; it does less well where the climate is warm or hot year-round, as it is in the southern parts of that valley. Poplars grown in year-round warm areas often give an impression of similar maladjustment. Also, *Acacia nilotica*, a very important multipurpose species for irrigated forestry in India and Pakistan, is not uniformly frost resistant: it displays provenance variation in relation to frost damage. With a few exceptions, e.g., some *Pinus* and *Cupressus* species, conifers cannot stand high temperatures over sustained periods to the extent that many hardwoods can.

Sometimes, species are selected for very specific purposes, e.g., maximum fibre yield from very short rotation, irrigated, production systems. Dickmann (1975) listed some criteria for the ideotype for these systems:

- Rapid juvenile growth;
- Growth over a long growing season: thus, albeit in rainfed plantation practice, *Pinus radiata* is preferred to Douglas-fir in less temperate areas of New Zealand, to which they are both well adjusted, because it grows 11–12 months of the year whereas the latter does so for only about 6 months of the year and is therefore a lower volume producer;
- Single stemmed with upright excurrent growth habit, i.e., a high degree of apical dominance;
- Steep branch angle, resulting in a narrow crown: there is a parallel here with types that are sometimes favoured in agriculture;
- High shoot–root ratio;
- Easy to establish and regenerate, e.g., by coppicing;
- Acceptable wood properties; and
- Freedom from damaging insect pests and diseases.

Important examples of special purpose species are represented by those that tolerate saline or alkaline conditions of soil or irrigation water, or both. Many of these are indicated in appendices 2 and 3. Species such as *Acer negundo* that have strong, dense root systems are sometimes recommended for binding the banks of unlined canals. Conversely, negative selection factors are often appropriate. Thus, some species have a spreading crown habit that renders them unsuitable as subjects for high-yielding plantations although they can be valuable for other applications. Most *Albizia* and *Terminalia* species are of this nature. Plants that sucker or seed themselves strongly are sometimes undesirable, particularly where they can be invasive weeds in agricultural lands or tree plantations. Gaur and Barney (1968) mention *Robinia pseudacacia* as a strongly suckering species. Others are certain poplars (e.g., *P. alba*) and *C. glauca*. Among species that have become weeds in irrigated plantations are *Morus alba*, *Prosopis cineraria*, and *Prosopis juliflora*, as seen in the Indus Plain in Pakistan where their seed is distributed by birds and goats. Species that encourage seed-eating birds by providing shelter and good nesting sites, e.g., the multipurpose *Acacia nilotica* in sorghum-growing areas of the Gezira project in Sudan (Jackson 1976) and in grain-farming lands in the Indus Plain, are sometimes shunned (as, indeed, trees in general often are for this reason) by farmers. Counterclaims are sometimes made that birds will damage crops in any case because they fly long distances to feeding grounds, or that they do as much good by feeding on insect pests as they do harm by eating the grain. However, species less attractive to birds, e.g., most *Eucalpytus* species, are available, if required, and if they are acceptable in other respects. Damage by grain-eating birds is sometimes minimized by genetic manipulation of the crop plant to render the grain in the ears inaccessible to birds.

From review of the literature, there emerges a distinct "short list" of consistently high performing species that are versatile in relation to environments, water quality, and cultural practices and productive of high timber volumes and sometimes forage, gums, and latexes or tanbark as well, i.e., economically very attractive, multipurpose species. Some of these species, with published information about growth rates, are listed in appendix 1. Important among them are *A. nilotica* (syn. *arabica*), of which there are several subspecies (Brenan 1983); *D. sissoo*; several bamboos (e.g., *Dendrocalamus strictus* and *Oxytenanthera abyssinica*); several *Eucalyptus* species

(*E. camaldulensis*, *E. microtheca*, *E. tereticornis*, and *E. resinifera*, for example); poplars (e.g., some *Populus* × *euramericana* clones), provided there is a dormant season and no salinity; *Sesbania grandiflora*; and, for sheer toughness in face of heat, salinity, and even alkaline conditions, *Tamarix* species, particularly *T. articulata*. In closed plantations, these species usually do best in pure stands: only rarely do species mixtures seem to succeed in irrigated plantations. An exception is *Broussonetia papyrifera*, the dwarf mulberry, a shade-tolerant small tree that does well under *D. sissoo* or *A. nilotica*, e.g., in the Indus Valley. The shade-bearing characteristic of the first of these three species enables it to mix with the other two. Even here, however, the tendency of the understorey mulberry to form thickets must be controlled. Also, it cannot be grown under the overstorey species without detracting in some degree from the production of the latter and must, therefore, be capable of compensating economically for this.

It is important to guard against the uncritical use of a species that is successful under one set of conditions in areas to which it is less well adapted. There is a tendency for this to be done, e.g., with *E. microtheca* in Sudan where it is biologically attuned to irrigated conditions on the clay soils of the Gezira area but is less thrifty in the light sandy soils along the Nile in northern Sudan, e.g., in the Shendi–Atbara area.

There is always room for introducing additional species, or replacing those currently in use with better ones. In some cases, this is a priority need and programs to introduce and test new subjects are needed. Opportunities for beneficial efforts in this regard come readily to mind. Thus, partly as a result of recent exploration and supporting biological and taxonomic work by Australian specialists, including Barlow (1983) and Johnson (1980, 1982), opportunities are opening up to exploit the potentially valuable gene pools represented by the four genera of the Casuarinaceae in South and Southeast Asia, Oceania, and Australia. The success of *Casuarina* species in windbreaks and shelterbelts under irrigation in Egypt and Thailand suggests that there is a much greater potential for use of this genus in irrigated areas. Hall et al. (1972) have listed a number of dry-country Australian species, particularly *Acacia* and *Casuarina* species, among which are some of potential value for irrigation; Pryor (1953, 1970, and other reports not specifically referenced here) has recommended a range of *Eucalyptus* species for trial; the genus *Malaleuca* seems to warrant review for species of potential importance; the central and southern African *Colophospermum mopane* is potentially valuable for fine textured soils of high pH in hot areas (Armitage et al. 1980). The latter reference and Palmberg (1981) list *Acacia* and other species that warrant consideration to expand the gene pools available for irrigation and that are at present the subjects of widespread provenance trials under an international program of genetic exploration and testing sponsored by FAO and the International Bureau for Plant Genetic Resources (IBPGR).

Felker et al. (1983) have demonstrated important genetic differences with respect to growth under irrigation between individuals and provenances as well as closely related species of *Prosopis*. They measured biomass production of 32 accessions of *Prosopis* (mesquite) after 3 years under a range of irrigation intensities in the dry zone of Texas. Differences due to different irrigation treatments were small. However, there were 20-fold differences in growth between some of the accessions. The highest production (13.4 oven dry t/ha per year) was from a *Prosopis chilensis* collection from Argentina.

There are well established strategies and guidelines for introducing and testing species for particular applications, including the all-important beneficial exploitation

of provenance variation within species. Burley and Wood (1976) give guidelines for such work and Bosshard (1966e), Jackson (1976), and Sheikh (1978) are among those who emphasize the need for testing to check the transferability of species, provenances, or clones that have proved satisfactory under one set of conditions to others.

Criteria of particular interest in relation to testing species and provenances for irrigation in arid areas include their ability to achieve high levels of production, tolerance of salinity, economy in the use of water through stomatal mechanisms that reduce evapotranspiration, and ability to withstand high temperatures throughout the year (NAS 1974). Ahmed (1977) and Bosshard (1966c) have noted that the dreadful stem form of all but recently introduced *E. microtheca* materials in the irrigation projects in the Sudan can be attributed to inbreeding depression because all the seed could be traced back to a single tree. This emphasizes the importance of adhering to well tried genetic principles and procedures when introducing new species, varieties, or provenances. So also does the confirmation of important provenance variation among *Eucalyptus* species growing under irrigation in Niger (Barbier 1978; Delwaulle 1979), as well as in the Sudan (Bosshard 1966c) and in many other countries as documented, for example, by Pryor (1953, 1970).

In situations where water for irrigation is scarce or where its supply might decline or be interrupted at any time in the future, it would usually be prudent to select species that are not necessarily among the highest volume producers but are capable of giving higher yields, i.e., growing better, under irrigation but which would not fail when irrigation is withdrawn. One such species is *A. nilotica*.

Tolerance of waterlogging and salinity

There is a wide range of tolerances of salinity and associated waterlogging among plant species. This is illustrated, for example, by the lists of salt-tolerant species in appendices 2 and 3, which are based on testing by Firmin (1968) in Kuwait and Boyko and Boyko (1968) in Israel. Australian workers are finding much variation between and within provenances of *Eucalyptus*, including *E. camaldulensis*. The subject was reviewed by Arar (1975) for Saudi Arabia and Quraishi and Khan (1979) for Pakistan. Kramer (1949) noted that tolerances vary in relation to different ions. Yadav (1980) reviewed some saline-tolerant species in India in relation to ameliorative treatments using gypsum, nitrogen and phosphate fertilizers, and manure. Tomar and Yadav (1980) noted that tolerance of salinity can vary with the stage of development, i.e., from the seedling to the tree stage. Plants that are sensitive to salinity are called glycophytes, tolerant ones halophytes. Some halophytes accumulate salts in their tissues: examples are *Salvadora persica*, *Tamarix aphylla*, *Melaleuca leucodendron*, and the doum palm.

Salinity that affects plant growth may be that in the soil or it may reach the plant through accumulation on the leaves and shoots, as in sprinkler irrigation with saline water (see chapter 3). Three factors related to soil solutes can influence growth and yield under saline or alkaline conditions:

- Reduced water potential of the growth medium (osmotic effect) affects plant growth directly;
- Accumulation of toxic concentrations of specific ions or imbalance of nutrients in the plant (specific ionic effect) affects plant growth directly; and
- Physical deterioration of the soil as a result of high concentrations of exchangeable sodium (alkali effect) affects plant growth indirectly.

In general, plants that are most sensitive to salinity, such as many deciduous trees, are also sensitive to specific ion toxicity. Thus, for the same total ion concentration, salinity due to sodium and chloride ions is more harmful to such species than salinity due to calcium and sulphate ions. More tolerant species can tolerate high salt concentrations regardless of the ions involved. In this case, the osmotic effect is the main factor that would affect their growth.

The dominant ions in the soil are sodium, calcium, magnesium, chloride, sulphate, bicarbonate, and carbonate. The most common types of salinity are those due to sodium and calcium chloride and sulphate. Bicarbonate may also be injurious and salinity problems may also be caused by high concentrations of other ions such as nitrate applied as fertilizer or by small increases in the concentrations of micro-elements such as boron. Salinity produces many symptoms similar to those caused by drought: affected plants are smaller and have a lower shoot–root ratio; the leaves are smaller and become a deep bluish green; and, in some cases, necrosis and leaf burn occur.

Salts can affect plant growth in four ways: by reducing water uptake, upsetting the hormonal balance within the plant, damaging plant cells and their contents, and increasing respiration and thus reducing photosynthesis. The factors affecting tolerance levels are complex. They are usually explained by physiologists in terms of variability of salinity and exposure of plants to it in time and space, soil chemical and physical conditions, and climatic conditions, e.g., the effects are stronger under high temperatures and low air humidities than the converse. In practice, salinity effects are reduced through selection of appropriate species and varieties, use of irrigation and water-treatment methods that prevent excessive salt accumulation in the root zone, and leaching salts out of the soil with sweet water.

Four methods are used for testing plant growth responses to salinity: salinity surveys of soils in relation to crop yields; field experiments comparing salinity levels, irrigation frequencies, and amounts and leaching intensities in relation to growth; artificially salinized plots; and pot experiments (Meiri and Shalhevet 1973).

Root systems

Available information indicates that rooting habits and development vary primarily according to species and are dependent also on the characteristics of the soil profile and the soil water regime, as modified by irrigation. Some investigators have reported that citrus species, for example, have shallow root systems. However, this may simply be a reflection of the fact that plant roots tend to respond to soil depth and to grow into and develop in moist areas of the soil; in deep soils, citrus manifests its typical main development in the 0–90 cm zone whereas the root system as a whole reaches down to 150–180 cm. Some plants, e.g., many annuals and, among desert trees, *Acacia tortilis*, do in fact have shallow root systems that do not extend much below 30–50 cm, whereas others extend beyond 300 cm.

Poor soil aeration leads to development of shallow root systems, which might account for the fact that, on river terraces along the Niger, the root systems of young trees are better formed in light than in heavy soils (Barbier et al. 1981). According to Bielorai (1973), Bielorai et al. (1973), and Ali (1960), the relations between soil water, root development, and yield can be defined generally as follows:

- Soil-water deficiency results in relatively large root volume and low yields;

- Adequate soil water is associated with moderate root volume and high yields: and
- Excessive soil water results in poor aeration, small root volume, and low yields.

It has been found that, in citrus trees, 85–90% of total water uptake is extracted from the main root zone and only 10–15% from the deeper layers (Bielorai et al. 1973). In a study by Rawitz et al. (1966), leading to the determination of the best irrigation regime for poplar in sandy loam to loamy soil in a 600-mm rainfall area in Israel, it was found that uptake was uniform down to a depth of 120 cm, the percentage of the total in successive 30-cm layers from the surface downward being 32, 25, 26, and 17%. In this instance, it appeared that root distribution, as indicated by its activity, was relatively uniform throughout the profile.

A valuable series of observations and conclusions resulted from root studies by Bosshard and Wunder (1966) in the irrigated plantations at Gezira and the Khartoum Greenbelt, in both of which wide furrows between ridges are used. They excavated 140 root systems representing nine species. In summary, their conclusions for the species studied were

- *Azadirachta indica*: well developed root system if irrigation is not excessive, poorly formed if it is.
- *Albizia lebbek*: good, strong root system of medium depth. Tap root absent if its development is affected by seedling stage development in polythene pots.
- *Conocarpus lancifolius*: if planted on flat ground, root systems prolific, deep, and strong. In furrow irrigated areas, less deep and confined to the ridges.
- *Eucalyptus microtheca*: on flat ground, systems deep and strong with long roots. In furrow irrigated areas, root system tends to be strong but less deep and tends to keep to ridges. Can be much affected by polythene seedling pots.
- *Eucalyptus camaldulensis*: a fairly shallow root system. No tap root unless conditions for its development are favourable. Strong, long roots keeping to the ridges between furrows. Some indication of provenance variation in root development.
- *Eucalyptus tereticornis*: strong root system with tap roots of medium depth. These features are less marked under irrigated conditions.
- *Eucalyptus gomphocephala*: shallow, weak root system in irrigated areas.
- *Eucalyptus rudis*: well developed but shallow root system.
- *Prosopis chilensis* (locally called *P. juliflora*): strong, deep, dense root system typical of some drought-resistant species.

The general conclusions of the investigators were that, under furrow irrigation, the root system is long and narrow in plan, conforming to the ridge pattern. Maximum and average depths are reduced, presumably by subsoil waterlogging. These features reduce drought resistance and wind firmness. This tendency is paralleled by trends in *D. sissoo* and other species under trench irrigation in the Indus Valley of Pakistan and is confirmed by FAO (1969). The concentration of roots in the interfurrow ridges increases root competition there for nutrients, and for water when it is scarce. All species, especially the more valuable ones (e.g., the first two *Eucalyptus* species listed above), are very sensitive to overirrigation. As indicated in the notes on individual species, there is a general weakening of the entire root system under such conditions. The authors recommend adoption of irrigation methods in which trees are grown on the flat, and not along ridges in a ridge–furrow pattern, so that the roots can develop in all horizontal directions. If furrow irrigation is used, full overall saturation at each

application, i.e., overirrigation, should be avoided. Irrigation schedules should be sensitively adapted to weather, soil conditions, species characteristics, and the stage of development. Planting stock with roots that are malformed, e.g., by being grown in polythene pots, should be avoided and nursery production should be arranged accordingly. In furrow-irrigation areas, thinning should be done with due respect to the fact that root competition occurs among trees along the ridges and not across the furrows.

Tree growth and wood quality

Very little published information is available on the influence of irrigation on wood properties and quality. This impression was recorded by Nichols and Waring (1977).

Briskin and Murphy (1970) studied wood properties of 24-year-old *Pinus resinosa* after 4 years of irrigation with 25–50 mm of sewage effluent per week. The lower rate caused significant increases in tracheid length, tangential tracheid diameter, and cell-wall thickness. However, the higher rate had no effect on tracheid dimensions but produced a significant decrease in cell-wall thickness.

Nichols and Waring (1977) studied wood specimens from a 26-year-old *P. radiata* stand 5 km west of Canberra where supplemental irrigation and artificial drought conditions had been applied for 11 years, beginning when the stand was growing vigorously and about to close canopy. They found that ring width increased with the application of supplementary water and decreased under a partial drought treatment. The increase due to irrigation occurred mainly during the summer and autumn whereas the reduction from partial drought took place in the spring. Neither treatment affected spiral growth of the wood. The partial droughting caused severe water stress throughout the growing season, increasing minimum density and latewood ratio and reducing maximum density. Irrigation, on the other hand, being most effective in summer and autumn, resulted mainly in an increase in maximum density. The expression of these components in the complex of average density was a slight increase for both treatments. The slight changes noted were not expected to affect wood utilization adversely. The results generally confirmed a previous study by Nichols (1971) with the same species grown near Adelaide in South Australia where trees normally grow under some stress during the summer. Supplementary water was applied at a rate of 25 mm/week during summer and autumn. This resulted in sizeable increases in diameter increment and an increase in the proportion of thick-walled cells associated with summer and autumn growth.

As noted in chapter 3, the empirical trials of 45 species under irrigated conditions in the low veld of Zimbabwe included the investigation of basic density, fibre length, and sawing, seasoning, and peeling trials based on a one-tree sample from each of the 15 most promising species. The utilization properties were compared with general utilization standards for wood of the same species grown under rainfed conditions and indicated that the materials were acceptable for such purposes as sawing, peeling, and transmission poles. Basic densities and fibre lengths did not appear to depart unduly from those for normally grown wood. Whether grown under irrigation or not, *Eucalyptus* species are usually regarded as being eminently suitable for pole and usually also fuelwood production, poplars for peeler logs and production of match splints, *D. sissoo* and *Anogeissus leiocarpus* sometimes superior to others for shelterbelts and fodder production, and *Khaya senegalensis* as well as most of the foregoing for sawtimber. *Acacia nilotica* is considered to be valuable for all these purposes (Barrett and Woodvine 1971).

Socioeconomic Feasibility

Given the need for tree products in arid and semi-arid areas, the fact remains that land and water for producing them under irrigation are scarce and that the competing needs for agricultural production are nearly always overriding. Nor are the scales tipped in favour of use of the basic resources for forest plantation by the fact that fuelwood — the principal product usually required from irrigated plantations in these regions — is a low priced commodity. Indeed, in some regions, e.g., eastern and western Africa, the attitude of many is that fuelwood has no true monetary value because, at the natural woodland source, it is god-given. The economic case for irrigated tree plantation is strengthened, of course, when building and other poles, sawlogs, fruit, and fodder are produced. Pricing policies — which are subject to periodic, sometimes sudden, change — can affect the situation, as they do in the case of the currently lucrative production of *Eucalyptus* poles in preference to food on irrigated agricultural lands in the Indian state of Gujarat (see chapter 3 and later in this chapter).

It is not surprising that, in the face of some of the foregoing facts and factors, among others, it is increasingly common to use various forms of integration of tree plantation with irrigated agriculture. Yet enormous problems of fuelwood supply, linked with natural woodland depletion and desertification, remain. Agroforestry, the opportunistic use of parcels of nonagricultural land for tree growing, and the multipurpose use of water are frequently and quite seriously stated to be inadequate strategies for wood production, particularly fuelwood. Block plantations are regarded as essential components of production strategies in a number of instances, e.g., Pakistan and Sudan.

In the economic assessment of alternative strategies for the use of scarce basic resources at the policy-formulation stage, due allowance should be made for nonquantified costs such as the true, full cost of water, the possibility of long-term effects such as induced salinization causing tree and agricultural crop decline, as well as indirect benefits, e.g., those that would arise if irrigated plantations take the pressure off depleted natural woodlands. A further factor that would sometimes be relevant, as it has been in India, is the possible effect on the market of the sudden advent of large quantities of wood.

Economic evaluation of alternatives, to select the most feasible and the least costly system in relation to the benefits sought under foreseeable conditions, may be based on assumed levels of effectiveness of inputs (including managerial inputs) and outputs that are not attained in practice. It is important, therefore, that such evaluations should be as realistic as possible and allow fully for risks and unfavourable factors. One strategy for achieving realism is to review post-facto assessments of actual projects to determine what factors can turn out to be unfavourable; what can go wrong; the areas requiring special analysis and attention in design, implementation, operation, and management; and built-in safety margins and flexibility. An encouraging feature of most assessments is the optimism that is expressed that in spite of the errors and omissions of the past: success — that is, an economically favourable outcome — is attainable provided certain deficiencies are made good (Hagan et al. 1968; FAO 1972; IDRC 1981). It might sometimes be salutary to make the analyses, or parts of them, on the basis of units of water rather than of money.

In the present context, major economic assessments of irrigated plantation projects for which the results are available are those of the Gezira plantations (Foggie

1967; Ali 1979) and that of the government plantations in the Indus Basin (Lerche and Khan 1967). Also of interest are the economic analysis for certain of the latter plantations (Khan 1966); the analysis for irrigated plantations in the low veld of Zimbabwe (Banks in Barrett and Woodvine 1971); that for irrigated farm plantations in Gujarat (Gupta 1979); and unpublished IBRD analyses for initial developments in Niger (Hamel 1985).

Foggie (1967) reviewed the enormous unsatisfied demand for wood in the area served by the Gezira project. He noted that the rates and regularity of watering of the plantations were variable, the amount given very often being much less than was required for optimal growth, that management was unrealistic in several other ways, and that the prices charged for wood were subsidized. He concluded, without taking into account any environmental benefits, that the indications were such that, if the foregoing deficiencies were corrected, the plantations would show a profit even if the interest rate on the investment was 10%: this was better than the poorer agricultural crops. If the plantations could be managed so as to attain something more like potential productivity, the return would equal that of the best cotton growing areas. Ali (1979) concluded from his assessment some years later that the plantations in general were commercially profitable and economically viable as well as socially desirable. He analyzed several sets of management alternatives, e.g., comparisons of coppice and seedling regeneration procedures and different rotation lengths in relation to high, medium, and low site indexes, and indicated those that would enhance returns. Bayoumi (1976) made a theoretical calculation of the benefits, in the form of water saved by reduced evaporation, that would accrue from planting a system of shelterbelts in the area totaling the equivalent of 8400 ha of block plantations (1.5% of the area of the whole project). He estimated the amount of water that would be saved at about 400 million m^3/year, enough to irrigate a further 33 600 ha of cotton. Wood yields would be extra.

Lerche and Khan (1967) concluded from their wide ranging analysis of the management and economics of irrigated government plantations in the Indus Basin that, in general, the returns from them would compare favourably with those from agriculture, particularly irrigated rice and sugarcane, provided that a range of technical and plantation management changes was introduced so that wood production could be rendered optimal or nearly so, that water rates were not increased, and that uneconomic small blocks of plantations were liquidated. Khan (1966) appraised then-existing water utilization practices and concluded that considerable upgrading of results could be expected from improved and more sensitive and efficient design, practice, and management in this respect.

With regard to prospects for irrigated plantations along the Niger River in Niger, Barbier (1978), after reviewing the results of (and some of the difficulties encountered in) early trials with *Eucalyptus* species in the area, concluded that there could be no doubt about the economic soundness of such a venture, given a good water supply at reasonable cost and a tract of reasonably fertile land free of salinity. Six years later, after attempts to establish an operational project in the area, in spite of a number of difficulties that had been encountered, some of which occasioned high unforeseen costs, Jean Gorse (World Bank, Washington, DC, USA, personal communication, 1984) concluded that it was reasonable to expect forest plantations in the bottomlands to show a favourable internal rate of return of 10%, equivalent to that of irrigated rice, or about 5% on the less favourable river terraces, provided that the costs of water could be kept low and provided also that a high degree of effectiveness of the technologies applied could be maintained. However, Hamel (1985) was less sanguine. He believed

that, at least until the remainder of the indigenous wood resource has been used up, the economics of irrigated plantations would compel integration with agricultural production as the only sensible course, particularly in view of the need to foster personal involvement and commitment of those most closely involved in the field, i.e., the people themselves.

The potential for irrigated plantations in the low veld of southeastern Zimbabwe was described and put into regional economic perspective by P.F. Banks in a short note that he contributed to the paper by Barrett and Woodvine (1971). The case for irrigated plantations of fast-growing species to produce fuelwood and poles for local use was seen as a largely local matter for which cost-and-benefit data were now available. However, any question of plantations for industrial purposes such as saw- and veneer logs, pulpwood, or transmission poles would bring in wider economic considerations. The main economic industrial plantations in the region are located in limited high-altitude, high-rainfall areas that contribute much of the water yields of important river basins. This has led, in some cases, to restriction of plantations in these highly productive upland areas. The high potential for production of wood for local use, as well as for industrial use, in a wider context was unquestionable. To the investor, the economic advantages of irrigated plantations were seen to lie in the short rotations that would apply, coupled with high financial returns. Production costs would exclude those of costly fire protection and would be further reduced by rapid canopy formation as well as easy working conditions in the flat terrain of the plantation areas. Disadvantages would be the high cost of preparing the land for irrigation and the cost of water. The economic viability of irrigated plantations would hinge on the relationship between these partly compensating cost factors on the one hand and high yields from short rotations on the other. An analysis indicated that the higher discounted costs per unit volume of wood produced in irrigated plantations at low elevation would probably be more than offset by the appreciably higher yields per unit area produced here compared with the best plantations grown on similarly short rotations in the high-elevation, high-rainfall zone. There could be no doubt about the economic benefit of growing narrow belts of trees on seepage areas and along canals among irrigated cane and other crops. In such cases, there would be little or no cost attributable to tree growing arising from irrigation network construction or water use.

An optimistic note in respect to the returns that are possible from irrigated *Eucalyptus* "hybrid" grown for the production of poles was struck by Gupta (1979) in his financial analysis of a 65-ha tree-farm enterprise a few kilometres south of Ahmedabad in Gujarat. The area was formerly used to produce agricultural crops on a sandy loam soil with slightly brackish irrigation water. Planting began in 1971 and the trees were clear felled at 5 years. Early indications were that the first coppice crop grows more rapidly than the initial seedling one. There was a firm, assured market for the poles. The analysis was based on one seedling and three coppice rotations, each of 5 years, although it was believed that five coppice rotations would be possible. Without taking the value of the land into account, the financial rate of return (see chapter 9) was estimated at 129% for the initial crop and 213% for each coppice rotation. When land values were included in the analysis, these returns became 36 and 61% respectively. They represented an appreciably higher return on the investment and operating costs than those experienced for agricultural crops on the same land. A disadvantage was the higher use of water by the tree crop.

Pryor (1953) and Veltcamp (nd) concluded that, in irrigated areas in Iraq and the Jordan Valley respectively, poplar plantations were economically more attractive than annual crops on the less fertile areas. Veltcamp predicted that this feature would

become more general in the Jordan Valley as a result of intensive vegetable cropping over extended periods.

The concensus among all these analysts is that, with certain important provisos in respect of management, plantation forestry is economically feasible and, in certain circumstances, at least as attractive as poorer agricultural crops and sometimes at least equal to the best of them. From a review of these analyses, it is clear that, given sound technical approaches, among the most important inputs for economic feasibility and success are the management ones. In many developing countries, technical skills to conduct irrigated tree plantation initiatives are lacking. This is an important reason why Hamel (1985) contends that full integration of tree plantation with irrigated agriculture is the way ahead in Niger and more particularly Sénégal. At least in the initial phases, feasible measures should be taken to make tree growing as attractive to the farmer as rice or sorghum production. The farmers would require training and support through extension services. From the beginning, it would be made clear that their interventions and commitments to the work are of overriding importance. As always, success of the strategy would require assessment by specialists of the sociological factors that bear on the matter — for example, land tenure; the customs, perceptions, and expectations of the people concerned in respect of crop, animal, and tree husbandry; and their views regarding the latter in particular. It would be established, for example, why they are not already growing trees, what experience they have of such activity, the reasons for whatever success or failure attended these efforts, and their preference for species, including fruit-bearing trees. The sociological analyses should be undertaken at an early stage to obviate, for example, the promotion and use of species that are objectionable to the people concerned. In addressing the matter of involving individual farmers in tree growing on their own account, it should be borne in mind that some people, particularly peasant farmers, are not accustomed to ventures that entail long-term investments.

Decision Criteria for Forest Plantation Development

The headings of the sections of this chapter provide a checklist of most of the criteria for decisions as to the feasibility of irrigated plantations in any particular instance, be it uniform plantations or integration of trees with agriculture.

- *Does a demand exist for tree products and influences*? Fuelwood, poles, special woods, fodder, fruit, tannin, honey, sericulture, pharmaceuticals, environmental amenity, and soil fertility and fixation.
- *Can irrigation play a role in production*? Can trees grow without water? Would trees grow appreciably better under irrigation?
- *Are land and water available*? Quality, quantity, reliability, cost, and competing demands.
- *Is the scheme technically feasible*? Irrigation and silviculture.
- *What is the environmental impact*? On land, water, and human health.
- *Is irrigation socially feasible*? Land tenure, cultural environment for tree planting and irrigation, availability of managerial skills.
- *What is the economic feasibility*?

7. Development of Irrigated Plantations

Forms and Scale of Irrigated Plantations

The view is widely held that there is limited scope for the development of new large-scale irrigated forest plantations. This stems from the consideration that financial yield prospects are not optimal in view of the low price of the materials produced after rotations of several years in relation to the high development costs entailed. Also, long crop rotations imply greater risks than annual cropping and, as already noted, the competing needs of agriculture are usually regarded as overriding. On the other hand, economic arguments involving broad, unquantified benefits, or foreseeable major cost reductions, such as the reuse of industrial water, are advanced in support of large-scale block-plantation schemes. Each case should be judged on the basis of realistic financial and economic analysis.

The alternative of integrating tree growing with irrigated agriculture is attractive for several reasons. It entails lower development inputs by taking advantage of the infrastructure needed for agriculture, promotes the multipurpose use of water, maximizes use of the site without necessarily reducing (but often actually increasing) annual crop yields, can promote early returns from the tree crops, and enhances the benefits of primarily agricultural schemes. In schemes comprising large numbers of small-scale farms, tree growing by farmers would be based on small-scale individual initiatives, which, in aggregate, could be regarded as being equivalent to large-scale programs. It must be noted, however, that such programs can be subject to failure due to the very smallness of their components, a feature that might weaken them in various ways so that things can go wrong too easily.

Agroforestry is not necessarily restricted to low-input technology and its practice introduces complexity into the operation of a farm. For this reason, guideline materials are required to optimize applications of this type of production, in which the tree component can take several forms for which there are quite specific technical approaches. At the same time, the plan must accommodate such facts as that, in an intercropping system, one component is the priority one and that provision must be made for the agricultural components to be rotated. In other words, the tree components and their management should be integrated in a coherent manner. Pilot-scale schemes are necessary to optimize and demonstrate designs, species selection, and silvicultural methods.

Land Use and Tenure

With the possible exception of small individually, corporately, or sometimes publicly owned schemes, the land use and tenurial aspects of irrigation developments are of basic relevance and are profoundly important. They represent real, long-term

interests of people and introduce sensitive sociological considerations that cannot be ignored in the planning and conduct of irrigation projects. Glesinger (1960) pointed out that the principal obstacles to successful irrigation schemes have been sociological, having to do, among other things, with land tenure and fragmentation of land holdings. It is necessary to ensure that the perceptions and concerns of the people in these matters are accounted for fully in project planning and management. This would normally entail specialist inputs to establish the essential sociological parameters.

The installation of an irrigated forestry plantation scheme, whether on its own or combined in some way with agriculture, involves commitment of land, water, and capital costs, complex technical and service inputs, and acceptance of an indefinite time dimension. Such commitments compel a high degree of ecological security through technical control, e.g., to prevent waterlogging and the development of soil salinity. Without the support of the people who have a basic interest, e.g., some perception of ownership, in the land involved or affected, all these elements of a successful project can be jeopardized. In discussing the ingredients for successful forestry programs in general in India, Swaminathan's (1980) stress on the need for forestry to become "a people's movement" applies particularly to irrigation forestry, which is likely to be practiced on their land frequently as part of some form of agroforestry. The full control of the government over all water in Israel, as explained by Schechter (1977), would not be sustainable without the active approval, through participation and benefit, by the people. The wish of local farmers to participate is the basic criterion for the selection of villages to participate in irrigated tree plantation development in an agroforestry setting near N'Debougou in Mali under an IDRC-supported project aimed at alleviating the serious local shortage of fuelwood and poles.

A farmer establishing a windbreak to protect his field from blowing sand by planting one or two Prosopis *trees in each small irrigated basin along the windward margin — he got the idea from a nearby IDRC-assisted land-reclamation project.*

The realities must be recognized of existing land tenure systems, traditional methods of crop rotation, and customs and needs in respect of the depasturing of domestic stock. Changing or in any degree impinging on custom in these respects entails a need for participation and support of the people involved. In well conducted policy formulation and planning, implementation, and management of irrigation projects, such sociological aspects are accounted for fully along with the technical and economic factors. The people involved are consulted and their support sought in appropriate ways at appropriate stages, from the earliest. Their concerns should be among the parameters that are subject to monitoring under the managerial system for the project.

The foregoing remarks do not in principle imply any lack of validity of investment in large-scale block plantation schemes provided, however, that they are soundly conceived and that they also meet appropriate economic, technical, and sociological criteria as to soundness.

Physical and Ecological Survey

Detailed soil and topographic surveys are required for the design and implementation of irrigation systems. Before these begin, however, it is necessary to know the general features and conditions of the landscape, such as those given by relatively small-scale maps (1 : 250 000 or smaller) that depict general physiographic, geographic, broad ecological, and infrastructural features. In relation to infrastructure, it is prudent to ascertain not only the existing features but any that are planned and that might affect the project. Records of land ownership, with supporting maps and plans, are also relevant. Existing geological and soil survey data are assembled as part of the basic information set. In many countries, these surveys include important data about the general features of landscapes and groundwater. A good example is that of the data on soil salinity and the quality of shallow saline aquifiers in karstic regions of southern and central Australia discussed by Holmes and Colville (1970).

Features of topography and soil that are relevant to the design and implementation of irrigation systems have been discussed in chapter 4. The relevant sections should be read in conjunction with the discussion of soil and topographical surveys that follows.

The soil surveys recommended by FAO and in the outline of Yaron and Vink (1973) for agricultural irrigation design and management are undertaken in three successive stages. (Aerial photographs are particularly useful for the first two.)

First, a preinvestment or reconnaissance stage at a scale of 1 : 100 000 to 1 : 250 000 to show physiographic units and associations of great soil groups and soil families, individual soil families, and phases of soil associations and families. During this stage, soil units are related to irrigation suitability units.

Second, a semidetailed feasibility stage using map scales of 1 : 50 000 to 1 : 100 000 to show associations of soil series, physiographic units, individual soil series, soil complexes and types, and phases of associations.

Third, a detailed design and execution stage, in which map scales may be as detailed as 1 : 2000, to show soil series and types and phases of them, and contours at intervals of 1 m or less.

At the first or second stage, it is often helpful to undertake an ecological assessment combining for the interpretation physiographic and topographical fea-

tures; surface or shallow-horizon indications of soil physical, drainage, and chemical conditions; and pointers given by plant indicators such as halophytes and glycophytes, i.e., information of value as guides to the design of the silvicultural systems of the project, including species selection.

For semidetailed soil surveys at the feasibility level, the scale used will vary according to the extent of the area under consideration and the size of the sample surveyed, probably 5–15% depending on the extent of the area of interest. A series of interpretive maps is derived from these surveys to depict irrigation suitability and soil quality and possibilities for soil improvement and suitability of the soil for various irrigation systems and crop types.

Detailed soil surveys for design and implementation need not always be undertaken for the whole area, but they should be done for sections where soil improvement or special irrigation management are required.

The hierarchy of surveys described and the detailed nature of the data collected may appear to be idealized. However, references in the literature to problems that are encountered after irrigation begins suggest that surveys and assessments of the nature described, which normally cost not more than 2% of the total cost of preparations for irrigation, are not out of place. Wood (1977) urged against piecemeal approaches to irrigation design and implementation. Clearly a deliberate, adequately intensive, analytical approach to design and implementation of costly arrangements that are to stand the test of time is fully warranted. Finally, it is clear that foresters do not have the technical background to act alone in these matters: they need the assistance and support of soils and irrigation specialists.

Assessment and Development of Water Resources

It is axiomatic that the water available for irrigation should be assessed as to its quantity, quality, and reliability of supply before the design and implementation of an irrigation development is attempted. Among other things, selection of the most appropriate irrigation system depends on a proper evaluation of available water supplies (Buras 1973a). Cases sometimes occur where water supplies are found to be inadequate after implementation has begun. The circumstances causing such disruption are usually unforeseen but, because the result can be destruction of the project, the need for caution should there be any doubt as to the reliability of supply is apparent. This point is frequently recorded in the literature, as are instances of lack of care in checking the characteristics of water supplies before projects are committed.

A number of specific instances of irrigation water-supply characteristics and actual assessments have been discussed in chapter 3, e.g., in Mali, Niger, and Zimbabwe. Booher (1974) emphasizes the need not to be dependent on water that is diverted from a stream, the flow of which fluctuates seasonally. If watering, e.g., by hand from a trailer, is to be done for 1 or 2 years after planting to encourage tree roots to develop until they reach groundwater, its existence within reasonable range of the root system, and the nature and magnitude of its seasonal fluctuation, should be checked.

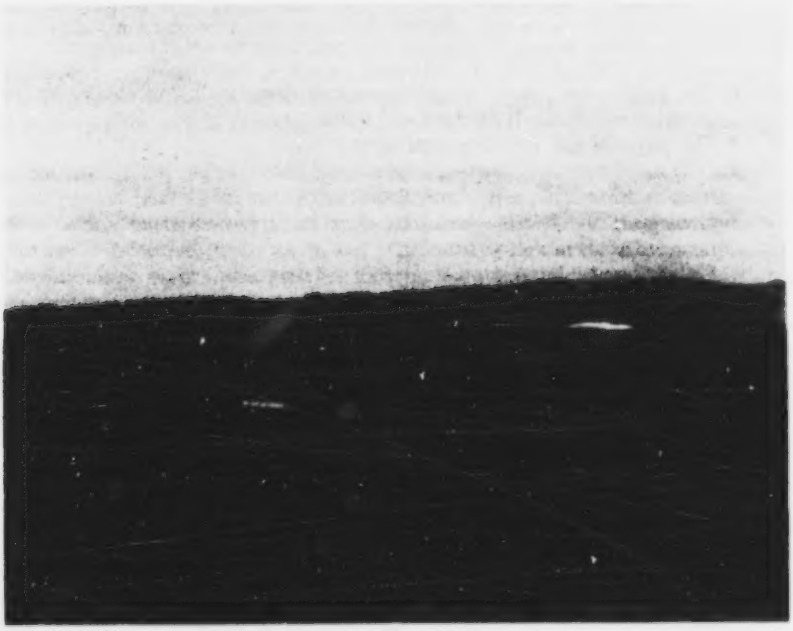
The information required for planning and management of water supply for irrigation requires detailed, deliberate survey and assessment as to quality and quantity; seasonal, diurnal, and any other variations in availability; reliability in both the short and long term; plans for changes in quantities, sources, or distributional arrangements in the future; and costs.

As in the case of soil survey and assessment, foresters do not usually have the specialized knowledge to undertake water analyses and assessments of the types required alone. Specialist inputs should normally be sought, particularly in the assessment and planning phases.

Buras (1973b) discusses several matters pertinent to development of surface and groundwater supplies. Streamflow and groundwater, which are often tapped and stored in reservoirs, fluctuate not only seasonally but also from year to year — the ranges of such variability being narrower in temperate than in arid regions. In the arid zone, flow along a water course can vary within a year from thousands of cubic metres per second to nothing. It can vary similarly from one year to another. These features introduce into each case a degree of hydrologic uncertainty that occasions much complexity in design, including the need to provide for risks of shortages.

In many areas, groundwater provides the bulk of water supplies for irrigation, industrial, and domestic use. An important characteristic of such water resources is that they can be developed in a much more gradual manner than surface water. Thus, well yields can be expanded as the demand increases, leaving little pumping capacity idle for extended periods. This contrasts with the large investments necessary to expand surface water supplies, developments for which are often, perforce, constructed to meet future projected demand and are therefore underutilized for a time.

The management of groundwater resources is concerned to match the supply with demand or vice versa, at the same time minimizing the possibilities of degradation of the resource in quantity and quality. An important management concept is,



Temporary irrigation in progress: Mule-drawn water tanks being filled from a bowser for watering newly planted Acacia cyanophylla *in central Tunisia.*

therefore, that of "safe yield" when exploiting an aquifer, i.e., the amount that can be withdrawn annually from a groundwater basin without exceeding its sustainable flow.

Again, the conceptualization, design, and management of groundwater supply systems on any scale is a specialized undertaking, requiring inputs by specialist hydrologists.

Design of Irrigated Production Systems

Irrigation systems and water regimes

To be successful, an irrigation system must meet the primary requirements of optimum economic return, economy in the use of water, and indefinite sustainability of fertility and productivity of the site. Achievement of these tenets depends in large measure on a design phase in which full account is taken of all the pertinent economic, social, physical, chemical, and biological factors that bear on the project. Because each of the factors concerned is variable, each system as designed will have its own unique set of features. This being so, the design package would not be complete without a detailed set of guidelines and schedules for its implementation and operation. Bearing in mind the indefinite life of the project, sufficient flexibility should be built into the design to accommodate changes in technology, cropping patterns, and irrigation schedules that are virtually certain to be required in the future. The design task is thus one of great complexity, requiring input from specialists in a number of fields (Lerche and Khan 1967; Yaron et al. 1973; France nd).

The first step in the design process, before attempting to come to grips with technical features, is to assemble, analyze, and assess the information available on all pertinent aspects. This would include

- The policy and general socioeconomic setting, including competing and complementary needs for land and water;
- The physical and infrastructural setting;
- Data on all relevant climatic parameters, if necessary using data extrapolated from weather stations at some distance from the project site;
- Geological and hydrological features of the area and at the source of the intended water supply;
- Soil, soil water, detailed topographical, and site ecological survey information;
- Survey and assessment of water supply, particularly as to quantity, quality, and any variation patterns that can be foreseen;
- The materials or forest plantation influence, or both, to be produced; and
- General features of the intended tree crop that would affect the design of the irrigation system, i.e., general layout, principal species, silvicultural management system, rotation, and harvesting.

The method of irrigation would be selected on the basis of the characteristics, advantages, and disadvantages of the alternatives in relation to the conditions under which they would operate, and the need to conserve water and preserve soil fertility (see chapters 4 and 5).

Before the irrigation supply and delivery system can be designed, it is necessary to determine the irrigation sequence, and the field irrigation-water requirement for each part of the project (e.g., plantation compartment) during the period of peak use, so that the correct flow rates and capacities can be established for each part of the system.

Estimates of crop water requirements are used in the determination of seasonal and peak supply requirements for the irrigation project. In these estimates, full account is taken of effective rainfall, groundwater contribution, leaching requirements, and irrigation efficiency. For the design, as well as the operation of the irrigation distribution system, a detailed evaluation is made of the field or compartment supply schedules, starting at the lowest irrigation unit and building up to blocks of compartments, areas served by each lateral canal, and finally those served by main canals. Three sets of specific calculations are entailed: the amount and intervals of irrigation of each compartment over the growing season, the water-supply schedules for individual compartments, and the design and operation of the overall water-supply system.

The aim in practice would be to bring the moisture content of the soil throughout the rooting depth to field capacity, applications being made at rates and frequencies that would prevent the occurrence of wilting or, in the case of localized irrigation with saline water, to achieve these standards without extending wetted zones beyond predetermined depths. The irrigation schedules would be modified as necessary and refined when applied in practice, on the basis of continuous monitoring and adaptive research and testing.

The water supply and distribution system should have sufficient capacity to deliver the required amount of water to any point when it is needed, should include arrangements for accurate control of flow, should be such that soil erosion and seepage losses are minimal, and should be designed so that maintenance and weeding can be easily performed. The system should be convenient to operate without excessive amounts of labour.

The scale of irrigation schemes can vary greatly and most of the literature that relates to irrigation-system design is relevant to large projects. The guidelines given in France (1969) are thus particularly helpful because they relate to the design of small gravity systems such as those required by individuals or small groups of landholders.

Early in the phase of designing water supply and delivery systems, decisions must be made as to whether they will be open or partly piped, and what form any lining would take. These matters are of major relevance to the need to practice economy in the use of scarce and costly water, and to the need to prevent seepage that, apart from wasting water, would raise the water table, causing waterlogging and deterioration of the soil system through salinization. Trout (1979) noted, in respect of the Indus Basin in Pakistan, that 30–50% of the water that enters most unlined water channels at the head does not reach the fields. This results in excessive groundwater recharge followed by salinization. The loss rates were found usually to be slightly less than proportional to the usual flow rate in the channel, lower in channels that were most often used, highest in elevated channels, and very sensitive to changes in flow depth. Intake into upper bank soils was very high due to extensive rodent and insect burrows. The importance of avoiding the ill effects of seepage has also been emphasized (Kramer 1949; Doneen 1972; Booher 1974; NAS 1974; France nd).

The design and selection of inlet, outlet, diversion, check, drop, and flow control valves, vents, gates, and other related structures are described and discussed by Booher (1974) and NAS (1974).

In NAS (1974), it is suggested that, where feasible, supply systems that combine surface and groundwater sources should be considered. This authority also notes that,

although reuse of irrigation water, which is often practiced, may be perfectly in order, the greatest care is required to ensure that it is not saline.

Many authorities and much experience (some of it reviewed in chapter 3) emphasize that adequate arrangements for drainage to dispose of excess groundwater, arising from seepage or deliberate leaching of salts from the soil, is an essential component of virtually all successful irrigation projects. Elevation of the water table through excess irrigation or seepage of irrigation water from unlined canals brings about saline or alkaline soil conditions (see, among others, Khatib 1971; Doneen 1972; Costin and Dooge 1973; Unesco 1974; Eckholm 1975). Doneen (1972) points out that, in heavy soils, impermeable horizons can occur that quickly form perched water tables, which have the same effects. He points out also that, if the water table rises above the zone of illuviated clay accumulation in the lower soil horizons, it takes up salt with it, to the detriment of plant growth. The effect is exacerbated when water moves up the profile through capillarity to evaporate at the soil surface because only pure water is evaporated — i.e., it is virtually a distillation process in which pure water is evaporated and the salts remain behind, to accumulate in the soil. Dan (1973) used the valleys of the Nile, Tigris, Euphrates, and Indus as examples to illustrate the fact that floodplains receive fine silt in water originating from high-rainfall areas in their catchments. This silt impedes soil drainage and thus tends to cause salinity, so that well planned drainage systems are necessary to maintain fertility, particularly in the lower parts of these valleys. The drainage should be installed at the beginning: to fail to install a drainage component usually results in very costly reclamation measures (Unesco 1974).

According to Shalhevet (1973), when natural drainage conditions are satisfactory, as when soil and water-bearing aquifers are permeable or the water table is at great depth, artificial drainage may not be required. If the natural conditions are limiting or a rise of the water table into the root zone can be expected, provision for drainage should, however, be included. Three principal factors should be considered when designing drainage systems.

First, the permissible depth to the water table, either permanently or temporarily, will depend on the soil or crop but would usually be 150–180 cm. Where seepage from outside sources or percolating rainfall is likely to raise the water table sufficiently to permit capillarity and evaporation at the surface, the water table should be at least 150–180 cm deep in medium textured soils. It can be less for sandy and clay soils but should be more for silty soils. Cointepas (1968), Van Hoorn et al. (1968), and Arar (1975) point out how critical the depth can be in Tunisia when brackish water is used for irrigation.

Second, the quantity of excess irrigation water to be removed depends on the amount of leaching necessary to prevent soil salinity — the leaching requirement, which can be calculated. The amount of leaching caused by rainfall should also be taken into account.

Third, the physical characteristics of the soil, principally those that determine the hydraulic conductivity of the soil, can be measured.

Elgabaly (1971) recommends protection against seepage from all sources and directions with drainage arrangements that will remove excess irrigation water from the soil within 48–72 hours of application and that include an effective, acceptable means to dump the water so removed.

Design would include detailed prescriptions and specifications for land grading, water supply and distribution including border checks and the like, and the road system including culverts and bridges. Land preparation, particularly if furrows or borders are to be used, must be done with precision and much care. It must ensure, first, that site fertility is not impaired by depths of cut that remove too much of the upper horizons so that saline, gravelly, dense, or otherwise infertile or impermeable subsoil is exposed or brought too close to the graded soil surface. This requirement is facilitated by detailed, accurate topographic surveys to provide the basis for selecting the most suitable slopes to which the land surface can be graded economically, and to obtain a proper balance of cuts and fills for the earth-moving work. Second, great care is required to achieve a finished surface that is uniform with respect to both slope and compaction so that water application and percolation are uniform.

Silvicultural systems and regimes

The selection of silvicultural system and, within it, the management regimes to be followed, are influenced by four complexes of factors, i.e., the products or influences required; the land-use setting and associated socioeconomic factors; the need to optimize economic results through efficiency of management and reduction of investment and operating costs; and constraints or opportunities implied in the prevailing environmental factors.

If the object of forest plantation is primarily to produce amenity or environmental effects, then the crop would take the form of individual trees, groups or rows of trees, or shelterbelts comprising two or more rows of trees, often interacting or integrated with other forms of land use. If the primary object is to produce fuelwood, poles, or timber, and perhaps fodder with one or more of these, any of the former configurations might be used in an agroforestry setting, or block plantation designs would be used, if associated forms of land use and economic considerations permit this. Shelterbelt plantations on the one hand and block plantations on the other are familiar features of irrigated projects. Wood and Synott (1978), in a proposal for the utilization of municipal wastewater in association with agriculture in Kuwait, provide an example of a program that combines both forms of plantation: high intensity *Eucalyptus camaldulensis* plantations at a spacing of 4 × 4 m grown on a rotation of 10–15 years to produce wood (fuel, poles, etc.); four rows of trees 20 m apart with trees spaced at 4-m intervals in the rows for general environmental protection near urban and industrial areas; and shelterbelts comprising three or four rows of trees spaced 2 m apart to protect agricultural and horticultural crops.

Integration of forest plantation into a land-use setting in which agriculture is overriding has been discussed in chapter 3 in relation to the United States and the Sudan. In discussing needs for fuelwood, poles, and landscape amelioration in relation to the Sudan, Foggie (1967) postulated a need for 7560 km of shelterbelts in addition to those that already existed and suggested that the tenant farmers should participate beneficially in growing them. The Gezira area also provides examples of the impact of other forms of land use on the nature of plantation forestry, i.e., the use for the latter of strips and small areas of land not required for agriculture. Similar examples have been noted in relation to irrigated plantation developments at N'Debougou in Mali (IDRC 1981) and near Niamey in Niger (Barbier and Louppe 1980; Hamel 1985). The use of irrigated block plantations of *Acacia nilotica* for soil improvement by farmers in Pakistan is mentioned in chapter 3.

Several authorities emphasize the importance of designing plantation systems that are straightforward to manage and involve moderate investment and operating costs, at the same time optimizing yields. In this respect, Khattack (1976) cautions against introduction of species such as *Prosopis juliflora* and *Prosopis glandulosa* that can be difficult to control and may become weeds, particularly if it is done misguidedly to replace an already successful multipurpose species such as *A. nilotica*. Ali (1979) discusses the relative merits of systems involving seedling and coppice regeneration in this respect.

The choice of silvicultural system, the nature of which is sometimes more or less imposed by primary agricultural use of the area, affects, in turn, the selection of species, regimes, and methods used. Species selection should be done to ensure, through careful matching to site and management conditions, that yields are optimal in relation to the objects of management (Laurie 1974). Thus, Lerche and Khan (1967) mention situations in northern parts of the Indus Basin where poplars can produce twice the returns of *Eucalyptus* species and where the former would be preferred provided that market conditions are favourable to poplar wood. The misuse of *Dalbergia sissoo* by planting it in markedly tropical areas, e.g., the lower parts of the Indus Basin, which do not match its need for an annual dormant period, or of inappropriate provenances of *A. nilotica* in upper parts of the same basin, where its growth might be affected by frost (see chapter 6), would not be conducive to maximum volume production. Tree types such as most *Albizia* species, *Azadirachta indica*, and *Terminalia* species would usually be unsuitable for optimum wood volume production because their typical spreading crowns tend to reduce stand stocking and wood production. However, they might be preferred where amenity and shade values are important.

The use of coppice systems, particularly where *Eucalyptus* species thrive and produce the required crop forms, is usually viewed with favour. One reason is that replanting costs are avoided for as long as coppicing can be practiced. Laurie (1974) and Gupta (1979) point out that yields from the first coppice rotation are normally greater and tree form better than from the seedling rotations and those from the second coppice rotation at least equal to the seedling rotation. In the Indus Basin, the management of *D. sissoo* stands according to the two-storey coppice-with-standards system has been a tradition for many years, the object being to produce fuelwood and poles from 20-year rotations of the coppice and valuable "rosewood" sawlogs from standards grown on a 60-year rotation. The system results in suboptimal yields through underoccupation of the site during much of the rotation, and is complex and not straightforward to manage, principally because the standards develop wide crowns that suppress much of the coppice. Moreover, particularly under the commonly used furrow system of irrigation, many of the standards develop root disease or are blown over long before they reach rotation age. The coppice-with-standards system can be applied successfully to *Eucalyptus* and other species that tend to have narrower or lighter crowns and that reach timber size in rotations considerably shorter than 60 years. In the Indus Basin, it also became traditional to grow one- or two-storey mixtures of *D. sissoo* with *Morus alba*.

Species mixtures, when combined with the coppice-with-standards system of managing *D. sissoo* already discussed, introduce further complications to the latter and can compound the detrimental results. Species mixtures can have the drawback of depressing overall yields (Lerche and Khan 1967), even if one of them (*M. alba*) is a shade bearer and the other (*D. sissoo*) light demanding (Ali 1962). Mixtures are

difficult to manage for a number of reasons, one of them being that, as in the case of *M. alba* and *D. sissoo*, the individual species have different growth rates (Hakim 1951). The current tendency, according to Khattack (1976), is to simplify management by converting mixed stands to single species, even-aged crops.

Lerche and Khan (1967) examined yields from *D. sissoo* plantations managed according to spacing regimes that had become traditional. Through examination of a series of alternatives, they demonstrated the importance of the length of the rotation on the production of materials required as well as on overall yields. More specifically, they found that the thinning normally done at 5 or 6 years was usually sufficiently heavy to ensure that the site would not be fully occupied for much of the remainder of the rotation, with the result that yields were below site potential. Thinning regimes should, therefore, be carefully devised in relation to the rotation to ensure maximum yields of the required produce (Lerche and Khan 1967; Sheikh and Raza-ul-Haq 1982a).

The important feature of optimum occupation of site throughout the rotation is also affected by the initial planting spacing and the alacrity with which the crop closes canopy and suppresses the grasses and herbaceous weeds that are encouraged by irrigation. It can also be affected by inadvertent introduction of tree and shrub species that become weeds, as in the case of *M. alba*, which has already been noted.

When forest plantation is integrated with agriculture, the two forms of production can interact in important ways. The beneficial effects that shelterbelts can have on conditions for the growth of the agricultural crop are well documented. Unless measures are taken to counter it, however, there is usually a depressive effect of the tree crop on adjacent rows of the agricultural crop. This is usually offset by benefits over the area as a whole that arise from the ameliorative shelterbelt effects. Indian farmers now commonly state that the depression of yields from rows of the annual agricultural crops adjacent to shelterbelts is more than compensated by the value of the timber or fodder, or both, produced by the trees. However, if this effect is undesirable, it can be controlled readily by plowing to leave an open furrow between the shelterbelt and the annual crop (Barbier and Louppe 1980; M.I. Sheikh, Pakistan Forest Institute, Peshawar, Pakistan, personal communication, 1983). Khan (1966d) and FAO (1969) reported that experiments at the Gezira project in the Sudan indicated some reduction of tree growth during the 1st year after planting as a result of competition with adjacent sorghum, maize, and grass crops; however, the effects were not measurable thereafter.

In agroforestry systems, intercropping of trees with annual or biennial crops usually entails only partial intertree interaction at most and the concept of a closed tree canopy does not arise. The trees are usually so spaced that they interact more with the agricultural crops than with each other. Because trees and agricultural crops normally occupy and exploit different parts of the above- and below-ground environments in different ways or at different rates, total production from a good agroforestry system is greater than it would be if the different components were grown separately.

Agroforestry systems development should, where possible, give the farmer options through which tree or annual crop returns can be maximized. Optimum early returns from the trees might result from high density plantations grown on short rotations. Alternatively, wide spacing of the trees would usually bring optimal early returns from the annual crops. Farmers normally require both high and early returns (Hamel 1985).

The actual conduct of forestry operations, as well as the nature of the silvicultural system chosen, should accord with the pattern of the agricultural activities with which they are meant to be integrated. The development of plantation techniques in such a setting at N'Debougou in Mali, as discussed in chapter 3, is an example. Procedures are being sought so that planting will be timed to follow rather than coincide with the busy season on the farm, while being timed optimally in relation to the seasonal cycle of flooding of the river and the rise and fall of the water table.

Features of the irrigation method can impose constraints on the growth and development of tree plantations and should be taken into account when designing either or both systems. As noted in chapter 6, when the furrow method of irrigation is used, root systems can be distorted so that the roots become more or less linear in the horizontal plane, sometimes resulting in stem deformity or in the trees blowing over. Lack of wind firmness can also occur with localized irrigation systems if the extent of the wetted zone restricts that of the root system, or if persistent overwatering results in the development of a shallow root system.

Trees in irrigated plantations, e.g., *D. sissoo* in Pakistan, can be very prone to root disease, especially if waterlogging is a feature or after use of the site for several decades. The condition is exacerbated when nursery stock with damaged or deformed root systems is used. Overwatering can be just as harmful to tree growth as underwatering and alternation of the two is often lethal. In this connection, Lerche and Khan (1967) cautioned that the area planted should never exceed that which the assured water supply can support.

8. Implementation and Production

Installation of Irrigation and Drainage Systems

However sound and comprehensive the design of an irrigation system, efficient long-term operation will depend as much as anything else on the care and correctness with which it is installed. In essence, this entails engineering and construction that will ensure ease of operation and control and, above all, uniformity of flow and application of the required amounts of water, with a minimum of unscheduled interruptions. Successful operation also depends on rapid removal by the drainage system of excess groundwater, whether this occurs inadvertently or through deliberate leaching. The requirements of a sound, practical design and an assured, reliable water supply are basic, yet they are not characteristic of all developments. Thus, Wood (1977) stressed the limitations that can be imposed by a piecemeal approach to irrigated plantation development and reference was made in chapter 3 to an applied research development on the Niger in which progress was frustrated for 2 years by the lack of a reliable water supply, resulting in 50% plantation failures during the first two seasons due to lack of watering (IBRD 1982).

Open water supply and distribution structures should be of uniform slope and cross-sectional dimensions so that flow, also, is uniform. Variation in the slope of pipelines is acceptable provided it does not result in hydrostatic pressure in excess of the operating pressures for which the pipe is designed. Gradients in unlined channels should not be such that they result in soil erosion. Shelterbelts should be established when necessary to protect canals from siltation by windblown sand. The banks should be stabilized. This has the added effects of maximizing flow and storage within the channel, reducing evaporation surfaces, and partially inhibiting weed growth. The costs of maintenance and weed control in unlined channels are always high and any feasible measures to minimize them are desirable. Leaks and spillage from pipelines and channels encourage weed growth. Open channels provide a ready means of distribution of weed seed throughout the system. Water in the channels from which distribution is done directly into the compartment has to flow at a level higher than the surface to be irrigated. Such channels should, therefore, have banks high enough to permit this when necessary, or be constructed in raised earthen levees.

In gravity systems, the ultimate distribution of water is controlled by the land surface itself and not by mechanical devices. Land grading is, therefore, the basic and most important operation in the construction of a gravity, or indeed any, surface irrigation system. The work entails a large part of the initial investment and, particularly in the case of perennial crops, defects are difficult to remedy once the system is operating. In a well designed system, the finished surface would not depart too much from the natural slope of the ground. Guidelines for land grading are given by Booher (1974) and Rawitz (1973b).

It is common practice in the Indus Basin for land grading to be followed by trial irrigation of the whole surface of the compartment, followed in turn by releveling and compaction of areas of consolidation and subsidence. This sequence is repeated until a uniformly consolidated, level surface is attained. Only then is the tree crop planted. Kramer (1949), Doneen (1972), and Ahmad (1975) stress the importance of avoiding lows that result in ponding and elevated areas that receive less water. Once the tree crop is on the ground, correction of levels is virtually impossible. Subsurface tile drains, at spacings and depths determined by means such as those proposed by Shalhevet (1973), van Hoorn et al. (1968), and Cointepas (1968), should be installed after the final grading but before the final surface compaction and leveling operations.

The irrigation furrows of gravity systems or the pipe lines of localized irrigation systems are sometimes sited on undulating ground, e.g., river terraces, without any prior land grading, or only after a minimum of it, to obviate the costs of earth moving. Jean Gorse (World Bank, Washington, DC, USA, personal communication, 1984) notes that, depending on the degree of irregularity of the ground surface, this practice can result in wastage of otherwise good land through use of a limited proportion of the area and inconvenience of working, with resulting increase in costs per unit area irrigated.

Tree Establishment and Tending

A comprehensive account of general tree establishment and tending methods is not necessary here because such information is available in numerous forestry manuals and texts. It is important, however, to note features or techniques that are pertinent to successful adaptation to irrigated plantation practice.

Nursery production

For plantations to derive maximum benefit from irrigation from the outset, nursery stock should be of good size for the species, not over grown, of high standards in respect of form and vigour, with well developed fibrous root systems free of root coiling, malformation, disease, or mechanical damage.

Physiological condition should be such that the plants can grow vigorously as soon as they are planted out in the field. The nursery operation should be aimed at producing stock, whether seedlings, transplants, root cuttings, or rooted cuttings, to predetermined specifications at the normal planting date. Cultural regimes should be developed accordingly and should include culling of plants that are not up to standard. Above all, stagnation of the seedling in the container or nursery bed should be avoided. On no account should undersized plants be held over in the nursery to grow on to standard size: they should be treated as culls and discarded. All too frequently plants spend too long in the nursery and thus lose condition by the time they are planted out. An example of a set of specifications to which nursery stock was required to be raised was that recommended for *Eucalyptus microtheca* in the Gezira plantations of the Sudan by Ahmed (1977) after he had conducted trials to determine the optimum plant for setting out in the field.

In arid areas, plants should be at least 30 cm tall when planted in the field. Smaller ones suffer too readily from blowing sand, salt (when that is a factor), and small browsing animals or grasshoppers.

Good quality nursery stock is rarely produced in containers that are closed at the bottom as this causes waterlogging and lack of aeration in the bottom of the pot. Also, roots soon coil in the lower part of the container. Although care must be taken to achieve a potting soil mix that does not fall apart too easily or harden excessively round the root, and care also has to be exercised when moving the pot to the planting site, it is preferable to use a tube with an open lower end, and to prune the roots that protrude there at regular intervals. This has been normal practice, for example, in the Sudan (Ahmed 1977) and Iraq (Pryor 1953). Growing plants in this way leads to the development of a fibrous root system that can be maintained in vigorous physiological condition. It also ensures that the root system is free of mechanical damage and thus not prone to root disease, to which irrigated soil environments are often conducive.

In hot areas or where nursery soil is inclined to be saline, watering should be done in such a way that a crust of salts does not form on the surface of the soil. Thus, if flood irrigation of nursery beds is practiced, care should be taken to flood to a depth that covers the soil surface in the containers, otherwise salts will accumulate in the upper part of the pot and the plant will suffer. Good drainage in the potting soil and laying-out beds is necessary to prevent waterlogging (Laurie 1974; Wood et al. 1975).

Rotted vegetable matter or manure is usually an ingredient of potting soil (Pryor 1953; Wood et al. 1975). Care should be taken to test and prove fertilizer treatments before applying them generally: nitrogen, for example, can be lethal to seedlings under some conditions (FAO 1969). Also, in arid areas, nursery beds are usually protected from dry winds and the sand that they carry by erecting screens round groups of beds and laying-out areas. Plants in polythene tubes or pots are prone to injury by high temperatures if their sides are exposed to the sun in hot areas: Wood et al. (1975) recommended placing banks of soil against the outer pots in bedding-out areas to prevent this.

Preparation of planting site: spacing

The traditional method of site preparation for planting in the Gezira and Khartoum Greenbelt schemes in the Sudan has been to use a heavy tractor-drawn plow to form a series of low, wide ridges 2.7 m apart, the height between the tops of the ridges and the bottoms of the intervening broad irrigation furrows being about 60 cm (FAO 1969; Laurie 1974; Jackson 1976). Foggie (1967) observed that it would be desirable, in the interests of uniform application of irrigation, to grade plantation areas before plowing and ridging them. The importance of starting with a well graded site is also indicated by experience in Pakistan (M.I. Sheikh, Pakistan Forest Institute, Peshawar, Pakistan, personal communication, 1984). Jean Gorse (World Bank, Washington, DC, USA, personal communication, 1984) referred to the difficulty of developing irrigated plantations in unleveled river terraces in Niger. In the Indus Basin of Pakistan, where irrigation has traditionally entailed the use of 20–30 cm deep, vertical-sided furrows 3 m apart, planting spot preparation, after grading, has been by cutting notches half way down the sides of the furrows to provide a planting shelf. Both here and in the Sudan, it has been observed that planting too close to the furrow results in malformed root systems that lead to leaning and windthrow of the trees.

For species trials using sewage effluent and untreated sewage water in Kuwait, trenches were made 0.8 m wide and 1 m deep, 6 m apart; alternatively, where trees were planted at wide spacings, pits 1 m cubed were dug. To reduce wind damage to young transplants, the trenches or holes were not entirely refilled with earth at

planting: the spare soil was piled on the northeast, i.e., the windward side of the plant. In other cases, shallow plowing of the site was done after ripping to a depth of 1 m at the intended planting spacing (Firmin 1971).

A special case of another kind is described by Khan (1966b) for establishment of *Acacia nilotica* by sowing in the floodplains of the White Nile. The floods, being seasonal, are predictable as to timing and depth. Ridges parallel to the direction of draw-down of the subsiding flood waters and protruding at least 30 cm above high flood have proved satisfactory, although 45- or 60-cm ridges give better results. In this instance, the species used (*A. nilotica*) is known for its tolerance of floodplain conditions.

In view of the relatively high costs of irrigated plantation practice, anything short of thorough preparation of an adequate hole for planting or a seedbed of good depth for direct seeding can hardly be acceptable. This is the attitude, for example, of Pakistani foresters in the flood or basin irrigated areas that now characterize most extensions of the Indus Basin irrigated plantations.

Pryor (1953) and Edgar and Stewart (1979), discussing irrigated plantation conditions in Iraq and (with municipal and industrial effluents) in northern Victoria respectively, mentioned the value of ripping in heavy soils or those with impeded horizons to render them penetrable to water and to improve soil drainage. Pryor suggested that, in coppiced *Eucalyptus* and poplar plantations, this operation might with advantage be repeated every few years during the life of a stand. The possibility of ripping was mentioned in the previous section in connection with land grading. It is often possible to apply this treatment while the heavy equipment necessary to do it is on site, having been used in the land-grading phase. The operation should preferably be done at the appropriate spacings in two directions at right angles to each other, the trees being planted at the intersections of the ripped cuts.

In the Indus Plain, the immediate seedbed for directly sown seed, e.g., of *A. nilotica*, is prepared on the graded, ripped land surface by including two or three tines for the purpose as part of the mechanical sowing equipment.

The spacing of the trees to be planted and therefore of the individual planting spots will depend on the purpose for which the trees are to be grown, the rotation, whether thinning is to be done and what the regime will be, and the silvical characteristics of the species to be used. In the case of plantations of mixed species, e.g., shelterbelts where two or more species are often used, the spacing between and within rows will be determined according to the growth rates and ultimate tree sizes of the species, as well as their silvical characteristics and the characteristics of the irrigation system to be used.

Plantation establishment

Field planting or sowing in irrigated plantation areas is invariably done when the irrigation arrangements are already in place or, in cases where hand watering is done for 1 or 2 years to enable plants to get their roots down to permanently moist soil layers, when the equipment for this is available (Wood et al. 1975).

Whether planting or direct sowing in situ is the method used usually depends on the species in use and whether the project takes the form of block plantations or individual trees or widely spaced lines of trees. Species such as *A. nilotica* that produce good quantities of seed that germinates easily when fresh and if pretreated,

and the germinants of which grow rapidly, are established by either method according to the preference of the grower. Direct sowing would usually be preferred using seed fairly liberally, particularly if this will produce forage or light fuelwood for which there is a demand.

For convenience of working with irrigation systems such as furrow irrigation, as well as when cleaning, weeding, pruning, or thinning, sowing is usually done in lines or spots along lines. Thus, *Prosopis juliflora* is being spot seeded (400–500 spots/ha) in the Bura Irrigation Settlement Project on the Tana River in Kenya. The relatively small number of spots per hectare reflects the difficulty there would be in cleaning young stands of this thorny species if the young trees were close spaced (N. Brouard, World Bank, Washington, DC, USA, personal communication, 1984). Broadcast sowing is frequently done in areas of flood or basin irrigation, e.g., with *A. nilotica* and *Sesbania grandiflora* in the Indus Basin, the seed often being broadcast into a maturing grain crop such as rice. There is no question about the difficulty of thinning out a young stand of thorny *Acacia* although this is minimized if the operation is not delayed, and the early yield of fodder and light fuelwood is a compensation.

Sowing trials were done in the Khartoum Greenbelt plantations in an effort to develop methods of establishing irrigated plantations that would entail lower labour use and costs than planting. Seed of five *Acacia* species, *Dichrostachys cineraria*, *Leucaena leucocephala*, *Parkisonia aculeata*, *Albizia lebbek*, and *Azadirachta indica* sown in spots at 2 × 2 m spacing did well enough for operational-scale trials to be recommended. Depth of sowing had little or no measurable effect on sandy clays but deep sowing on Nile silts slowed germination and spread it over longer periods than when shallow sowing was done. On such soils, depths of 0.5 and 1.5 cm produced better results than sowing 3 cm deep (Bosshard 1966d).

A third method of field establishment is insertion of unrooted cuttings. This is done with species that root easily, e.g., most *Tamarix* species, many poplars, most willows, mulberry, *Gleditsia triacanthos*, *Ipomea* species, and *Euphorbia tirucalli*.

This method was very successful with *Tamarix aphylla* cuttings 1–1.5 cm thick by 1 m long inserted 50–70 cm deep in 1 m trenches or pits in trials with sewage effluent and untreated sewage water in Kuwait. However, the cuttings tended to rot if moisture was more or less continuously too close to the surface (Firmin 1971). Bosshard (1966d) reported moderate results with the same species in the Khartoum Greenbelt plantations but poor results with other species, e.g., *A. indica*, *A. nilotica*, *Ceiba pentandra*, *E. tirucalli*, *Poinciana regia*, *Melia azaderach*, and *Peltophorum pterocarpum*.

Despite the fact that trials in irrigated areas in the Sudan (FAO 1969) indicated that planting *E. microtheca* with polythene pots left on the plants made little or no difference in good soil conditions, it is always best to remove the container immediately before planting to give the root system maximum freedom to grow out into the field soil. Care should be taken not to vitiate the whole purpose of using the pot by allowing the ball of earth round the root system to break up. However, any coiled roots near the base of the root ball should be opened out and preferably severed where they emerge from the earth ball. The polythene material, when removed from the plant, can be used either as a mulch round the base of the plant, or in desert or semi-desert areas, it can be wrapped round the stem to protect it from blowing sand (Wood et al. 1975). Protection from sand and browsing is often provided with palm fronds or thorny twigs, or both, inserted round the plant.

Planting with bare-root plants is sometimes done. In arid and semi-arid areas, however, the hazards entailed in handling and transporting materials of this kind over a period of some hours can be great and plants in containers are usually preferred. In trials in the Khartoum Greenbelt plantations, it was found that bare-root plants of *E. microtheca* could be used satisfactorily provided the labourers involved took sufficient care (FAO 1969).

Care should always be taken when transporting plants from the nursery to the field site to ensure that plants do not lose condition, dry out, or suffer disturbance of their root systems. They should be regularly watered if held for 1 or 2 days before planting.

Planting should be done after the soil has been moistened but, in hot areas, not during the hottest months (Pryor 1953; Wood et al. 1975). The Indus Basin, and more markedly in the northern parts of it, is an example of areas where there are two possible planting seasons: dormant stock of deciduous species such as poplars and *Dalbergia sissoo* is planted during the winter whereas physiologically active stock of evergreens is planted during the summer.

As noted in chapter 5, irrigation is sometimes applied only for one to two seasons after planting to enable tree roots to reach down to moist levels in the soil horizon. This may be done, as in the case of roadside plantations in semi-arid areas in Pakistan, by hand from water trailers or, as at N'Debougou in Mali (IDRC 1981), by means of temporary trenches along the tree rows.

It is important to ensure that plantations are fully stocked with successfully established plants at an early stage. A standard of 90% survival with evenly distributed successful plants is commonly used. Inspections and sample surveys should be done 4–6 weeks after planting and dead or unthrifty plants replaced if necessary, particularly if the failures are concentrated in different parts of the area.

Fertilization

The literature on irrigated agriculture contains a great deal of information on fertilization to enhance yields. Kalkafi (1973) notes that the choice of a specific fertilizer and the amount to be used in a given case of irrigated agriculture depend on the specific crop, the state and stage of its development, soil type and the nutrients in it, the time of application, and the cost. Change in nutrient supply through fertilization can significantly affect dry matter yields. Under a given amount of irrigation water, the transpiration ratio of a field crop can be changed as much as threefold by fertilization. Hadas (1973b) stressed that soil fertility is one of the more important factors that affect root development and that too much or too little nitrogen can have a critical influence. Workers in the field of agricultural crop fertilization often caution against the negative effects that some fertilizers can have on production under certain conditions, implying the need to test specific fertilization treatments before applying them generally.

By contrast with the agricultural field, the literature on both rainfed and irrigated culture of forest plantations contains relatively few references to fertilization and is largely devoid of descriptions of experiments aimed at determining economic fertilization regimes. This is the case in spite of the fact that nitrogen, phosphorus, and potassium fertilizers are commonly used in forest nursery production, and these and soil amendments to correct deficiencies of trace elements such as boron are frequently applied in rainfed plantation forestry. That added nutrients can have beneficial effects is illustrated by the assertions of, for example, Urie (1975), Edgar and Stewart (1979),

Alverson (1975), and De Bell (1975) that a "free" supply of extra nutrients is one of the reasons why the use of municipal and industrial effluents provides a development opportunity in the form of high-yielding irrigated plantation forestry. Studies of this topic are needed, beginning with empirical trials that would lead to the formulation of guidelines for the development of fertilizer regimes that might be tested for general application.

A somewhat unusual form of fertilization sometimes practiced in irrigated areas is the application of gypsum to soils affected by salinity. Gypsum provides a source of calcium to replace sodium and thus helps to reclaim sodic soils. It is used in this way in the Indus Basin in Pakistan. It is sometimes also used to treat saline irrigation water.

It is well recognized that organic matter (green manures, compost, and manure) plays an important buffering role if added to saline or sodic soils. It is used in the reclamation of areas affected in this way (Shah Mohammad 1978; Nishat 1978). Firmin (1971) observed that addition of sewage sludge to the soil in irrigated forestry trials in saline conditions in Kuwait was important for this reason.

Weeding and cleaning

Weeding is the removal of spontaneously occurring vegetation that competes with and then reduces the performance of the cultured crop. Cleaning, a term that is usually applied to a broadcast or naturally seeded crop, refers to the removal, usually in operations repeated two or three times at relatively short intervals, of surplus plants, leaving an evenly spaced residue (usually comprising the best and most vigorous saplings) to grow on and, as nearly as possible, utilize fully the potential of the site. The two operations are similar in some ways, including their being required several times in the first 1–3 years. They are usually carried out together. Neither should be delayed. Cleaning should be conducted in accordance with specific rules as to the average spacing to be attained between stems at stated stages from seeding or planting.

Although the number of plants per unit area of the crop being grown is controllable, at least to some extent, by the density of sowing, the population of weeds is not. Weeds arise from root systems in the soil that survive site preparation, from seed brought by the wind or birds (e.g., *Morus alba* in the Indus Plain) or goats (e.g., seed of *Prosopis* species in the same area), or by transportation in irrigation water. They thrive in the irrigated conditions and characteristically infest the banks and environs of water channels or any point along a pipeline where leakage occurs. Of course, they can thrive throughout the irrigated plantation area as well. Prominent among them are usually a number of rhizomatous as well as deep rooting grasses, but annuals, shrubs, and trees and even damaging climbers also occur. They grow rapidly and can seriously affect the growth of crop trees, often quickly stifling them if not controlled.

Simply slashing weeds by knocking them down is not a sufficient control method, at least in the early stages of crop development. Clean cultivation once or twice a year is usually important, particularly with trees such as *Eucalyptus* species that are notoriously sensitive to weed growth, especially grass, and especially as it competes for water. The importance of weed control in irrigated plantations is stressed by Pryor (1953), Ali (1962), Goor and Barney (1968), Booher (1974), Ahmed (1977), Ali (1979), and Edgar and Stewart (1979).

Weed control should be considered when developing plantation thinning schedules. It might be necessary, for example, to sacrifice some of the concentration of diameter growth that thinning directs to fewer remaining stems per hectare and to

retain a higher tree population to maintain a canopy that is sufficiently dense to suppress the weeds. Unfortunately, this is not possible with species such as most *Eucalyptus* species that present the edges of their leaves to the sun and thus admit light freely to the floor of the stand. In such cases, periodic weedings throughout the rotation may be necessary.

Stand tending: thinning and pruning

As a general rule, it is desirable to plant or sow at relatively close spacing, e.g., 2 × 2, 2 × 3, or 3 × 3 m, or to clean to such spacings after direct sowing, to ensure early and continuing occupation of the site by the crop and thus to maximize intermediate and final yields, and to maximize opportunities for selection, during thinning, of prime trees to form the final crop. Close initial spacing also provides early yields of small utilizable material from thinnings as early as the 2nd or 3rd year. An example of maximization of production in this way is sometimes seen in the management of sown *A. nilotica* in the Indus Basin and in India, in respect of which Kaul and Chand (in Kaul 1970) found that progressive spacing and thinning during the 1st, 2nd, and 3rd years resulted in enhanced diameter and height growth of the stand, and therefore in increased volume production both in the early years and in later phases of the rotation.

The thinning regime depends on the nature of the products or influences required from the project, the capability of the site, and the silvics of the species. The species must be carefully selected in relation to these factors. The thinning regime manipulates stand density through the rotation so that, through a reasonably practical frequency of thinnings, an optimum balance is established between continuous utilization of site potential, concentration of volume growth and quality on the final crop stems, and optimal intermediate yields. The kind of information that is required to determine the best regime to meet these criteria is illustrated by the results of a spacing study in *D. sissoo* reported by Sheikh and Raza-ul-Haq (1982a), in which spacings of 4 × 4, 3 × 3, and 2 × 2 m were tested in irrigated plantations. At age 4 years, it was found that mean stem DBH (1.2 m from the ground) and branch number, thickness, and length decreased whereas length of clear bole increased with closer spacing; quantitative data were ascertained for these parameters and for basal area and volume per hectare at each spacing to be used and were applied in the derivation of thinning regimes and for growth prediction.

The best parameter to use for the control of thinning at each stage is basal area. Number of stems per unit area can be used for this purpose provided that the basal area that this measure reflects for stems removed and remaining in each case is known. In furrow irrigation areas, it should be borne in mind that tree root systems are so aligned and organized that most below-ground competition occurs between trees along the rows and little or none across furrows.

It is important to monitor the growth of plantations through periodic measurement of growth parameters of representative samples of various crown classes to ensure that they are not stagnating for want of thinning.

Thinning of shelterbelts requires careful planning. It is an important feature of the management of such plantations to ensure continuing effectiveness of their intended function of acting as barriers to wind. For this purpose, species that regenerate from coppice are often included in the mixture so that renewal of foliage in the lower tiers can be done easily and rapidly. Coppice itself also requires management, whether in

shelterbelts, even-aged stands, or those managed as coppice-with-standards. In *Eucalyptus* stands, for example, the numerous shoots that sprout on the cut stump are usually reduced, by pulling them off manually, to about six per stool about 6 months after felling and, by cutting, to two or three after a further 6 months.

Pruning is done to provide access to plantations, especially where thorny species are used, to produce well shaped, clear boles and, in the case of sawtimber, an outer shell of knot-free wood. The branches make useful light fuel and the foliage can be used for fodder if required. To be effective, pruning should begin early in the life of the stand, e.g., at 2 or 3 years. Sheikh (1981) indicates the maximum degrees of live pruning of poplars in the Indus Basin that may be done without unduly affecting tree growth.

Water Management and Use

Rates and methods of application

The basis for determining crop water requirements was indicated in chapter 6 and for calculating and scheduling seasonal and peak irrigation needs and for designing the supply and distribution system in chapter 7. The number of interacting factors upon which these determinations depend is large and their relative importance varies according to the environmental situation, season, crop type, and stage of development. As noted earlier in this chapter, some of the requirements can be modified if fertilizers are applied. The aim in irrigation is always to use water efficiently, to optimize crop yields, and to maintain site fertility. Accordingly, as suggested in chapter 7, deliberate measures should be taken to refine the schedules as calculated by continuous monitoring, adaptive or applied research, and making and testing adjustments once the project is in operation. The approach to refinement and monitoring of supply schedules is described by France (nd) and Doorenbos and Pruitt (1977) who state that, in addition to refinement of supply criteria, the activity should be addressed to the hydraulic properties of the distribution system as well as the operation and management of them.

Adaptive research should be carried out on soils representative of the project area. The trials should comprise a carefully designed network: they should not take the form of a patchwork of unintegrated experimental plots. The program of trials should begin during the design phase and be continuous. Its nature and extent would depend on the availability of supporting specialists and the capabilities of the staff. To ensure inputs from a range of specialists, it might be carried out in collaboration with appropriate national research institutes. The studies and monitoring activities should include

- Evaluation of water aspects of field irrigation methods and schedules, crop types, and development stages;
- Studies of frequencies and amounts of irrigation;
- Development of leaching and associated cultural practices to control salinity;
- Studies of effect of irrigation scheduling and any periodic seasonal water deficits on yields;
- Studies of irrigation methods, including trials of alternative layouts, lengths of run, and permissible stream size; and
- Fertilizer trials, including irrigation–fertilizer interactions.

Guidelines for experiments and studies aimed at improving irrigation practice are given by Doneen (1972). The results of the trials would be translated into recommen-

dations regarding amount and depth of irrigation at different seasons and for different sites and crop stages. Irrigation schedules and operation of the distribution system would be modified accordingly.

Data should be collected continuously for climatic parameters (a full-scale agroclimatic station should be set up in appropriate instances), groundwater-level fluctuations, water availability and quality, and sediments. Routine investigations should be made of soil physical and chemical properties to monitor their changes under irrigation in case corrective action becomes necessary. Yaron and Vink (1973) stress that, because irrigation modifies all soil-formation factors, both qualitative and quantitative, monitoring them is an essential feature of efficient system management. Wherever appropriate, the studies suggested and monitoring would be done in relation to measures of tree crop performance.

It is best to irrigate immediately before wilting occurs and to apply just sufficient water to bring the soil throughout the rooting zone up to field capacity. Under irrigation, the soil is either wetted in a zone that expands with percolation over time or it is not wetted: if there is an area within the soil that is only partially wet, it is so because plant roots are working in it. Guidelines for the application of the correct amounts of water are given in the next section. It may be noted here, however, that inadequate watering of the soil reduces yields and, in conjuction with leaching, can lead to loss of nitrates. This was a problem in the early years of use of sprinkler systems in the USA and Israel (Kalkañ 1973; Shmueli 1973). In time, the irrigation schedules for a specific project should reflect sensitively the facts that sandy soils are irrigated more frequently and with less water each time than heavier ones; that water use varies with crop development stage; and that water use is lower in cool, cloudy weather than when it is clear, hot, and dry (Kramer 1949).

It is of interest to note examples of the amounts of irrigation water applied and other pertinent aspects of plantation irrigation projects in various parts of the arid world. In the Gezira project in the Sudan, no water is available during the hottest time of the year, from April to June, due to the effect of the Nile Waters Agreement with Egypt. A total equivalent to some 1240 mm is given by furrow irrigation to *E. microtheca* in 12 or 13 even applications, i.e., at 2-week intervals from July to

Runoff farming in the Negev, south of Beersheba, Israel: Well constructed dike along plantation margin traps and stores water from rare runoff events.

December (a period of moderately rapid height growth) and monthly from January to March, when height growth is most rapid (Masson and Osman 1963; FAO 1969; Bayoumi 1976; Ali 1979; Ahmed nd). These amounts and frequencies were confirmed in trials reported by Khan (1966a). However, Foggie (1967) thought that a total of about 1700 mm was required for maximum volume production.

In the Indus Basin, flood or basin irrigation, which uses larger quantities of water but is appropriate to areas affected by salinity, appears to be supplanting the elaborate traditional furrow layouts. Raeder-Riotzsch and Masrur (1968), Khattack (1976), and Ali (1960) have recorded that the irrigation schedules in use have been developed by trial and error, implying that they do not necessarily reflect the correct application levels for the species and sites used. Lerche and Khan (1967) found that 1370 mm/year, applied over at least 6 months straddling the summer, was about the average target of irrigation water application although the actual rates applied varied widely and the exact amounts were seldom known. Sheikh (1974a and personal communication, 1984) reported the results of trials of trench and flood irrigation that were undertaken and have been continued to the present to determine the optimal schedule for *D. sissoo*. Total annual applications of 450, 900, 1350, 1800, and 2250 mm have been tested in applications at 2- and 3-weekly intervals. There is a pronounced response in yields when the amount is 1350 compared with below 900 mm, growth being appreciably lower with lesser amounts and not noticeably improved with the higher quantities tested. Applications at 2-week intervals give better results in terms of growth than those every 3 weeks. Method of irrigation has made no significant difference. In general, these results confirm established practice. Trials with *E. camaldulensis*, *M. alba*, and poplars indicate that annual total applications of water as high as 1500 mm are usually excessive. A feature of the literature recording the results of this work is that no mention is made of adjustments in irrigation rates to take fluctuating rainfall amounts into account.

The rates tested in species and provenance trials along the Niger River in Niger (Barbier 1978; Louppe 1979) were equivalent to 250 and 500 mm/year, applied in the dry season. Both rates resulted in significantly more growth than rainfed conditions but there was little difference in growth response between them. This was believed to suggest that the trees were drawing on groundwater for some of their needs.

For trickle irrigation in desert conditions in Abu Dhabi, Wood et al. (1975) reported that 9000 L of water were required per hectare per day. There were 200 trees/ha so that each was to receive 45 L/day. The period over which irrigation was applied was not stated but over a 6-month period this would be the equivalent of about 1650 mm. The rates prescribed by Wood and Synott (1978) for three separate trickle irrigation schemes in Kuwait, reduced in the same manner, amount to equivalents varying from 1470 to 2940 mm.

In the winter-rainfall area of coastal Israel, Rawitz et al. (1966) found by experimentation that the optimum rate for two poplar clones under sprinkler irrigation was a total of 1350 mm/year, in addition to the prevailing average annual rainfall of 600 mm, applied in doses at 2-week intervals. Karschon (1970) found that *E. camaldulensis* under sprinkler irrigation at Ilanot (30 m altitude) with similar rainfall conditions did best if given 2000–2200 mm/year. An earlier, preliminary trial of summer irrigation had failed to provide a response because the species is dormant during that very hot, dry time of the year. The importance of the additive effect of rainfall on irrigation rates and through them on deep percolation and waterlogging is stressed by irrigationists, e.g., those in Israel, and should be taken into account in irrigation scheduling and management (Unesco 1974).

In the empirical irrigated plantation trials of 45 species representing 13 genera in the semi-arid low veld of Zimbabwe (Barrett and Woodvine 1971), a range of canal-side, directly irrigated, and seepage sites was used. Hand watering was done in most cases during the first few months after planting to ensure that tree root systems were brought into contact with moist zones in the soil. The various sites were assessed as to the nature and extent of water available to the plants. The duration of the hand-watering period and the irrigation or seepage-water characteristics were then used in the characterization of the sites used and to group the trial plots for analysis so that the results could be related to broad water regimes and extrapolated as desirable. Six watering regimes were recognized in this way, some being more favourable to tree growth than others.

Efficiency of water use: water losses

The efficiency of irrigation — the ratio between the calculated amount of water needed to bring the soil in the rooting zone to field capacity, which is what the irrigationist tries to do, and the amount actually applied — depends on the method of irrigation and skill in operation. If the amount applied grossly exceeds that needed for replenishment of moisture depleted by evapotranspiration, the efficiency of irrigation is very low. As noted in the previous section, application of less than the required amount of water can have undesirable effects on nutrients and results in suboptimal growth. Even with the best of controls, however, some water will be lost during irrigation, most of it through percolation below the root zone and small amounts may be lost as surface runoff, evaporation, or seepage from distribution channels. All these losses should be kept to a minimum, particularly if they go toward raising the water table but also because water costs money and nutrients can be lost with the water.

It is important to achieve the greatest degree of uniformity possible in the distribution of water across the area irrigated. Most irrigation methods do not permit so close a degree of control that water is applied for exactly the same length of time at one place as at all others, but all methods can be applied so as to approach this ideal. Guidelines for optimizing the efficiency of irrigation by conducting routine checks are given by Doorenbos and Pruitt (1977) and France (nd) who recommend the following procedures.

- Before irrigating, check soil moisture in the root zone at several locations; estimate the amount needed to bring it up to field capacity 2 or 3 days after irrigation.
- After irrigation, check soil moisture again, it should be close to field capacity throughout the rooting depth and there should be no dry spots or layers in the compartments.
- Determine the irrigation efficiency ratio, if it is unduly high or low, investigate and test.
- During an irrigation, watch to see whether the time during which water can percolate into the soil is more or less uniform all over the field or throughout the length of the area between border checks; whether basins and level borders are filled quickly; if furrows are used, whether the water reaches the lower end in about one-quarter of the total time that it occurs above the bottom of the furrow at the upper end.
- If runoff occurs at the lower end of a border or furrow, the stream at the input end is not being reduced or cut off soon enough; adjust the input stream in subsequent irrigations until something approaching even distribution is attained.

Under localized irrigation systems, there appears to be a minimum extent of wetted soil volume that is required for optimum growth. This volume is a function of the amount of water applied at each irrigation and it should be increased progressively as the trees develop (Doneen 1972; Vermeiren and Jobling 1980).

Provided that water supply is adequate, there is a general tendency to overirrigate to ensure that the plants receive enough water (Costin and Dooge 1973; NAS 1974). However, there is a limit to the amount of water that a plant can use (Clements 1934) so that the surplus is lost through deep percolation. This is always undesirable unless it is deliberately induced to leach out salinity in the soil. Deep percolation can also be brought about by nonuniform application of the correct total amount of water (Rawitz 1973a). It follows that, although it is important to know how much water is being applied to the crop, it is also necessary to monitor distribution over the land unit to which it is being applied. This was stressed by Chardenon (1979) after a measuring routine had proved invaluable in improving irrigation practice with poplars in Turkey.

Fast application of the required quantity of water, at rates consistent with the rate of percolation into the soil, is sometimes recommended because it reduces the time over which water lies on or moves over the surface and evaporates. However, it should be practiced with care because, in flood, furrow, and sprinkler irrigation, it could lead to runoff and erosion. In sprinkler irrigation, excessive water pressure for application aggravates wind drift and induces an aerosol effect, which occurs when the jet breaks up into very fine drops that are dispersed in the atmosphere (Rawitz 1973a).

Some evaporation loss from the soil surface is inevitable. However, it is undesirable because it leads to movement of salts up the soil profile and their concentration at the surface. Rawitz (1973a) recommends that judicious modification of irrigation schedules, by reducing the irrigation frequency and increasing the dosage per irrigation would curb upward salt movement.

Economy in the use of water and the overall efficiency of irrigation can be improved if a sensitive, flexible approach is adopted to system operation involving careful, continuous monitoring of water application and its effects. Any tendency for those responsible for supply systems to deliver water arbitrarily and inflexibly according to predetermined supply schedules should be discouraged. In arid areas where water is scarce and where evaporation from the soil surface is a serious problem, and where designs involve the use of single trees or small groups of trees, several devices are used to reduce evaporation or evapotranspiration, including the use of mulches such as cut foliage and other vegetation; covering the soil with flat stones, plastic, and other materials; removing unwanted transpiring vegetation, particularly phreatophytes; and using or breeding tree types that transpire at less than average rates. Reduction of water loss through evaporation is a major reason for planting shelterbelts (NAS 1974). Based on observations in the Gezira plantations in the Sudan, it was recommended that, in many situations, economy in the use of water, as well as avoidance of problems due to excessive irrigation, should be effected by irrigating only during a period of 2–3 months following the end of the rains instead of doing so throughout the dry season. This would have the effect of prolonging the rainy season (Nigeria 1957).

Maintenance of irrigation and drainage systems

The importance of thorough, regular maintenance of irrigation supply and distribution systems, from the main canal down to the ultimate distribution furrow or

other device, is axiomatic in relation to successful project operation. It begins and is facilitated by considering the needs of maintenance in the design phase so that weak points and the causes of problems can be removed in good time or at least minimized. As will be seen in chapter 10, provision for routine maintenance is a major function of project administration and management. Whether maintenance is effective or not is manifested in crop performance: it can be an overriding factor in either optimizing or reducing yields, i.e., the financial and economic results of the enterprise.

Thorough routine maintenance of main and lateral irrigation canals and channels or pipes delivering water to and within the individual compartments, and of control and outlet devices, is necessary to maintain a regular, uniform supply of water. Maintenance functions should be concerned particularly with points of consumption toward the lower end of the system, and with preventing losses by seepage from conveyance systems. Specific routine tasks include removal of accumulating sediments; repair of leaks, cracks, and other defects in these structures, including rodent and insect tunnels in earthen banks; removal of weeds; repair of damage to channel banks at points of abstraction of water; and regular attention to pumping and distribution equipment. It is important to schedule the work and the occasional unavoidable interruptions of supply that are entailed so that they do not disrupt irrigation schedules to the extent of reducing the growth and well-being of crops. In this connection, shutdowns of whole distribution sectors for a month or more are regular annual features of some projects, e.g., the Gezira project in the Sudan and some irrigation sectors in the Indus Basin. As often as not, they occur in the dry season and are usually timed in relation to the needs of agricultural cropping rhythms. Therefore, they can cause severe setbacks and damage to perennial crops that depend on water supply at the time. Such features should be borne in mind when analyzing the economic feasibility of proposed irrigated plantation developments and might even tip the balance against their being undertaken (Ali 1960; Lerche and Khan 1967; NAS 1974; Unesco 1974).

Effective maintenance of irrigation systems necessitates periodic surveys and monitoring of both the water used and the soils so that due attention can be paid to undesirable developments, e.g., those affecting drainage, before they become serious (Yaron and Vink 1973; Yaron et al. 1973; France nd).

It is appropriate here to mention the particular maintenance needs of localized irrigation systems because the small water passageways of distributors are susceptible to blockage. For perennial crops, these devices can be used to dispense up to 10 L of water per hour (Heller and Bresler 1973) so that lengthy stoppages can have serious consequences. The causes of blockages include sand, silt, organic matter, algae, bacterial slimes, and precipitation of salts and colloids. Vermeiren and Jobling (1980) quote the results of one survey of the causes of clogging as being biological (37%), chemical (22%), physical (31%), and uncertain (10%).

Clogging of such systems may be prevented by effective water filtration, use of self-cleaning suction filters and sand–gravel filters, and chemical pretreatment of water to prevent precipitation of chemicals or the growth of iron bacteria in the system. In the installation in an inland desert area in Abu Dhabi (Wood et al. 1975), a well trained labourer is put in charge of each module of 20–25 ha (4000–5000 trees). One of his duties is to check and maintain the trickle irrigation equipment by regular cleaning and removal of sand, dust, and other sediments. Pipes of polyvinyl chloride (PVC) or polythene materials are found to facilitate this as well as other aspects of the installations, and are therefore preferred to other materials such as metals. This point

has also been made by Jean Gorse (World Bank, Washington, DC, USA, personal communications, 1984) in relation to the installation and maintenance of localized irrigation systems in Niger.

Problems Related to Irrigation

Waterlogging and salinity

The development of soil salinity in irrigated soils where it has previously not been a problem, i.e., secondary salinity, results from several possible causes. It can be due to irrigation with saline water or a high evaporation rate that brings salts to the surface, in both cases without adequate allowance of water to leach salts down and out of the soil profile. Salts can also be brought into the rooting zone, and through evaporation ultimately to the surface, by a rising water table caused by overirrigation, lateral seepage from unlined canals, and inadequate drainage. Salinity, which may not always be associated with waterlogging, can occur very quickly in any of these ways. Each of them can be prevented or reduced, first, by correct system design and, second, by proper operation and various management alternatives (see chapter 6). These problems and methods of preventing or reducing them have been documented by many authorities, including Elgabaly (1971), Khatib (1971), Shalhevet (1973), Yaron et al. (1973), Unesco (1974), and Shah Mohammad (1978). Methods to offset the effects of irrigation with saline water are described in particular by Van Hoorn et al. (1968), Arar (1975), Wood et al. (1977), Vermeiren and Jobling (1980), and Yadav (1980).

The development of waterlogging and consequential soil salinity is associated with low-lying land, underground barriers to natural drainage, poor physical conditions and internal soil drainage (as in many floodplains and most deltaic areas), and low hydraulic conductivity of soils, coupled with insufficient rainfall to provide clean water for leaching. It follows that irrigation systems must provide the means to deal with these conditions, e.g., avoidance of overirrigation, provision of adequate water for leaching at suitable rates and intervals, and, above all, drainage to remove the saline leachates and excess groundwater, i.e., to control the water table. Problems can arise concerning the disposal of such excess, usually saline, water. The irrigationist must always know how much water is being used and its salt content. Waterlogging and associated problems and measures to counter them have been discussed and described by the authorities mentioned in connection with secondary salinity in the previous paragraph and by several others, including Dan (1973), Shmueli (1973), and Eckholm (1975). Trout (1979), in particular, describes reclamation of areas affected by raised water tables and waterlogging in the Indus Valley.

Measures to prevent the buildup of salts in the soil due to a rising water table and to deal with problems as they arise are built into the design and management of well planned and conducted irrigation systems in several ways:

- Water supply and distribution arrangements from which water losses are minimal;
- Flexible irrigation schedules that match the net quantities required to replace evapotranspiration and meet leaching needs, after taking effective rainfall into account;
- Site grading, construction of watering arrangements, and control of application of water that meet standards that ensure uniformity of irrigation in space and the proper amounts in time;

- Treatment of water to remove excessive salts when this is feasible;
- Leaching of excessive salts from the soil;
- Tile and other drainage systems to remove excess soil moisture rapidly and to carry it out of the area; and
- Effective monitoring of qualitative and quantitative changes in relevant soil and soil-water properties so that action can be taken to deal with problems that arise.

Localized irrigation systems, particularly those designed for the application of saline water, entail soil salinity hazards just as surface irrigation systems do. The salinity problems occur particularly at the margins of wetted areas, necessitating careful control of the extent of these. Leaching needs are met either by including sufficient water for the purpose on a regular basis, by periodic soaking of the site, or, in areas of Mediterranean climate, by partial soaking at the beginning of the rains and leaving the rest to the rainfall to accomplish. Depending on the amount and nature of the rainfall, supplementary sprinkler or surface irrigation may be used to accomplish all or part of the process.

The reclamation of affected areas and amelioration of secondary saline conditions should be dealt with by treating the system as a whole, concentrating primarily on removal of the basic cause and manifestations of the problem. Such operations can be technically complex and costly. In the first place, the sources of seepage water are sealed, e.g., by lining canals. Excess groundwater is removed by pumping from tube wells, removal of the water from the area, and leaching the salts out of the soil by flooding, i.e., rinsing it with "sweet" water. Leaching is most effective when the soil is unsaturated. The leachate must be drained away from the site. The process of salt removal, from either saline water or soil, is sometimes assisted by adding acid-forming chemical amendments such as gypsum, sulphur, or iron or aluminum sulphate. Yaron et al. (1973) point out that, in an efficient irrigation project, control of salt buildup in the soil can be facilitated by predicting the extent of salt accumulation and the amount of water that should be provided routinely to remove it.

Once problems have been checked and brought under control by these means, biological methods can be applied to bring the soil up to its potential productive capability. These may include green manuring or application of farmyard manure, compost, and the like to buffer the effects of the salts; growing soil-improving species, such as *Acacia* or *Sesbania* species to the same end; and applying supplementary fertilizer regimes designed by specialists. It is stressed that such measures are worth attempting only after the basic problems have been dealt with. Sheikh (1974b) records instances where the performance of ameliorative crops grown at this stage declined after 1 or 2 years because the basic problems had not been corrected. The overall strategy should be to apply a range of measures to reduce salinity to, and sustain it at, a moderate level. The use of salt-tolerant species does not solve a salinity problem, and species that accumulate salt in their tissues cannot reduce the salt level of the soil unless the tissues are removed from the site.

Root-system growth disorders and diseases

Root systems grow into moist areas in the soil. They tend to become less active if moisture availability declines and die off if the area dries up. Roots can withstand limited periods of waterlogging — some species, such as *A. nilotica*, being more tolerant of these conditions than others. In most cases, however, healthy root systems also depend on good aeration of the soil. These features have several implications for

irrigated plantation practice. If moisture availability fluctuates, the efficiency of the root system will be impaired, resulting in suboptimal growth. For this reason, uniformity of irrigation in amount and frequency is important. Lerche and Khan (1967) gave lack of regularity of watering as one reason for the lack of thriftiness of *D. sissoo* in some plantations in the Indus Basin, and Laurie (1974) noted that the same problem occurred at Gezira. Excessive watering early in the life of a plantation results in limited development of root systems in depth. This can result in severe windthrow and, if watering rates are subsequently reduced, wholesale deaths (M.I. Sheikh, Pakistan Forest Institute, Peshawar, Pakistan, personal communication, 1984). Vermeiren and Jobling (1980) recorded that if, under localized irrigation, the wetted rooting zone is too small, the spread of roots will be restricted and this would affect yields and the wind-firmness of the trees. For the same reason, trees under localized irrigation would suffer more stress if the water supply is reduced than trees growing under flood irrigation. Accordingly, the water supply for localized systems must be completely reliable and application regular.

Lack of soil aeration due to more-or-less permanent wetness, at least in areas immediately adjacent to the channels in furrow irrigated plantations, discourages root development there, so that asymmetrical root systems develop. If the lack of aeration covers a relatively large proportion of the area, and if irrigation is irregular, the root system has a "crippled" look. These features depress growth and wind firmness, can favour the development of fungal disease in the root systems, and cause death, as they did in *Eucalyptus* plantations affected in these ways in Iraq (Pryor 1953; Raeder-Riotzsch 1965) and at Gezira (Bosshard 1966a). Pryor suggested periodic ripping of the soil to about 2 feet (0.6 m) between the rows to encourage better percolation and rooting. Kadambi (1946, 1951) described root disease associated with the fungus *Trichosporium versiculosum* in *Casuarina* plantations in Mysore State in India and indicated that the conditions seemed to be due, primarily, to severe overirrigation alternating with withdrawal of irrigation for long periods.

Khan et al. (1956) described locally widespread damage to and deaths of *D. sissoo*, *M. alba*, and *M. azaderach* in irrigated plantations in the Punjab of Pakistan that were affected by periodic withdrawal of irrigation. The trouble was particularly severe in areas formerly occupied by clumps of natural forest. The organism associated with the problem was the debarking fungus, *Hendersonula toruloidea*. Khan and Bokhari (1970) reported infection of *D. sissoo*, *M. alba*, and *A. nilotica* by *Fomes lucidus*, *Poria ambigua*, and *Polyporus gilvus* following the same events in the Faisalabad area of the Punjab. *Ganoderma lucidum* is also commonly associated with butt and root rot of irrigated *D. sissoo* due to the same basic causes in the same region. Prevosto (1971) attributed severe attack of irrigated poplars in the Po Valley of Italy by the fungus *Marssonina brunnea*, which can significantly reduce growth, to interruption or irregularity of irrigation.

Some other aspects of root growth and formation in relation to irrigation are discussed in chapter 6. Like the problems cited as examples here, they also imply that the solution does not lie with direct control of the fungus or other such agency associated with the problem: the basic trouble lies with the irrigation method used and the manner of its use. In a sense, the fungal or physiological disorders are monitors: manifestations of them should be used in the monitoring and adjustment of irrigation systems, while the possibility of such problems occurring should, as far as possible be precluded when projects are designed.

Birds, insects, and animals

In areas adjacent to blocks of irrigated plantations or where tree cultivation is closely integrated with agricultural crops, as with shelterbelts or other agroforestry applications, farmers often object to the trees because they encourage the occurrence of flocks of seed-eating birds, e.g., finches, weaverbirds, and queleas in the Gezira, or are alleged to encourage damaging insects, such as some that affect cotton, or are alternate hosts to annual crop fungal diseases (Masson and Osman 1963; Jackson 1976; Barbier 1978). Similar complaints are made in the irrigated areas of the Indus Basin. The wise forester would pay serious heed to them, show concern and investigate each alleged case, and take corrective action in respect of cases that are valid, e.g., by selecting alternate tree species or suggesting measures to reduce the problem such as the use of crop types that frustrate the removal of the grain by birds. In at least one instance in Pakistan, it was claimed that allegedly destructive birds were doing more good by feeding on insects in a farmer's field than harm by eating grain.

Gerbil damage to agricultural crops and canal banks often follows the development of lush vegetation in irrigation areas (P.J. Wood, International Council for Research in Agroforestry, Nairobi, Kenya, personal communication, 1984).

There are few recorded instances of economic damage being done by insects on an important scale in irrigated plantations. Wood et al. (1975) mention that leaf miners, leafhoppers, and caterpillars harmed young trees in trickle irrigated plantations in the desert zone of Abu Dhabi, particularly when growth was lush during the hot season. The first two insects are controlled by systemic insecticides applied through the irrigation system. Belanger and Saucier (1975) also recorded the efficiency of applying insecticides with irrigation water, in that instance to control damaging insects in poplar plantations in the Great Plains area of the USA where the treatment was found to be more effective under furrow irrigation than sprinkler systems. Grasshoppers often do severe damage, as in parts of the Indus Basin. Durand (1958) also reported them as being a pest in young irrigated plantations in interior Algeria and Morocco. Termites can be troublesome, particularly if water is applied in reduced quantities in the dry season in hot areas. Mathur (1961) recorded termite damage in irrigated plantations of *Casuarina equisetifolia* in Rajasthan. It is readily controlled by insecticides such as aldrin (where use of such material is acceptable). Singh (1963) recorded that termite damage to irrigated plantations in the same state were controlled by applying infusions of tobacco or Aldrex 30E.

A disease (probably viral), known as "bayoud," of date palms in some North African oases is transmitted through groundwater (K. Oka, IDRC, Ottawa, Canada, personal communication, 1984). Although no such case is known to have occurred in actual irrigated forest plantations, the possibility of transmission of plant pathogens in this way should not be overlooked. The possibility of virological hazards arising in the same way as a result of the reuse of irrigation water is discussed in Unesco (1974).

Damage is sometimes done to irrigated plantations by browsing animals, e.g., goats and camels. In their proposals for plantations under irrigation with sewage effluent in Kuwait, Wood and Synott (1978) recommended that such damage should be prevented by direct control of the animals. This is normally done in the interests of annual crops in the Indus Basin. However, in the off-season, goats and cattle are released from their stalls or tethers and can harm young plantations. Apart from doing physical harm to trees by browsing them, they represent one of the agencies by which weed seeds, including those of unwanted tree species such as *Prosopis glandulosa*, are distributed.

Environmental and human-health implications of irrigation

Reference has already been made, in chapter 6, to the environmental implications of using for irrigation sewage and industrial effluents that contain minerals and ions that could accumulate in the soil and affect its productivity as well as the properties of underground water. The latter could seriously affect the potability of water through the buildup of nitrogenous ions (Alverson 1975; Urie 1975; Edgar and Stewart 1979). The downstream effects of irrigation-induced salinity and related waterlogging have been discussed in several sections, particularly earlier in this chapter. To these must be added any such implications of the use of fertilizers.

Irrigation areas, e.g., in Egypt, India, and Pakistan, are notorious for the parasites, including internal parasites such as those causing schistosomiasis (bilharzia) and malaria, and disease vectors, such as snails and mosquitoes, that can infest them. Among international agencies to which these problems are of direct concern are the World Health Organization (WHO) and the Land and Water Division of FAO on whose behalf Mather and Trinh Ton That (1984) undertook a detailed problem analysis and review of control strategies in relation to irrigated rice production. The main principles and strategies they discussed are relevant here. They noted that, although methods of disease and vector control through the use of drugs and insecticides are important, they are beset by problems of cost, vector resistance to insecticides, and their environmental and human-health effects.

These factors have led to the identification of other methods of vector control, such as environmental and biological approaches, that may be integrated with chemical methods. Control through environmental management entails three avenues of approach: through the use and management of water; through the nature and manipulation of the vegetation, including the crop; and through measures related to human habitation and behavioural patterns. Of these, the first two are of particular relevance to the irrigationist because vector and disease control or reduction features can often be integrated into irrigation and crop system design, operation, and maintenance. The authors emphasize the desirability of strategies that entail manipulation of ecological factors and thus, particularly in the long term, result in minimal chemical and overall cost inputs.

Fowler and Helvey (1974) examined the effect of widespread irrigation practice on local climate, using the Columbia Basin Project area in the Pacific Northwest as the study area. Examination of available records for July air temperature and July–August rainfall showed a very small response that could be attributed to the development of irrigation. Open-pan evaporation appeared to give the most sensitive measurement of the small integrated effect on the environment of the area. The investigators noted that ring width of the big sage brush, a particularly valuable plant for detecting change in the environment, especially improved water economy, remained stable throughout the development of the irrigated area. They concluded that, although microclimatic effects are more readily detected and site changes understandably occur, widespread climatic effects seem to be minimal.

Project actions can have important physical effects with serious social and economic implications that should, if possible, be foreseen and taken into account in the design or implementation phases of irrigation projects. This point is exemplified by the case, cited by Gittinger (1982), of the lining of preexisting canals with concrete to prevent further seepage. The action led to the drying up of wells in the vicinity that were dependent on that seepage and on which, in turn, people were dependent for their water supplies.

Growth and Yields

Rates of growth and yields have been reported for many irrigated plantation crops in arid and semi-arid areas and are of interest in indicating the very high levels of production that are possible under irrigation. The summary that is given here is of production in terms of utilizable volumes per hectare. Data in the form of height or diameter growth are valid criteria for growth assessment of young stands. However, they are excluded here because, in this context, they do not indicate production in economic terms and do not always permit valid comparisons between widely separated sites. The volume data that follow are intended to indicate general orders of magnitude of potentials for different species in representative situations. They should be read with caution because they are drawn from stands of different ages growing under a variety of environmental and management conditions and irrigation regimes. Some are based on careful mensuration, some are relatively rough assessments, and, as indicated, some are general predictions or informed estimates of what can be expected based on local results. (These data are summarized in tabular form in appendix 1.)

South Asia and the Middle East

India

It is unfortunate that volume production data are not available for a number of interesting projects, e.g., the tree farm near Ahmedabad in Gujarat reported on by Gupta (1979). However, some of them are referred to in terms of other economic parameters in the next chapter.

Yields of fuelwood from canal-side plantations of *Eucalyptus* "hybrid" under a social forestry project in Uttar Pradesh were conservatively expected to yield an MAI of 12 m^3/ha of fuelwood by 5 years; *A. nilotica*, *M. alba*, *P. juliflora*, and *Terminalia arjuna* yields in the same period were expected to be 6–8 m^3/ha per year.

Iraq

Prospects for production from proposed irrigated plantations on the Mesopotamian Plain were forecast by Busby (1979) on the basis of information then available from trial stands in the area. He believed that the following yields could be expected on the best sites: black poplar, 36 m^3/ha per year at 5 years and *E. camaldulensis*, 16 m^3/ha per year at 10 years.

Israel

In irrigation trials at Ilanot in the central coastal plain (30 m altitude, 603 mm mean annual winter rainfall) where *E. camaldulensis* is dormant during the hot dry summer, winter application of 368 mm of water in the 1st year, 538 in the 2nd, 593 in the 3rd, and 689 in the 4th resulted in an MAI at that stage of 14.3 m^3/ha compared with 7.2 m^3/ha in the unirrigated control. In a treatment that differed from the foregoing only in that the 1st year application was 192 mm instead of 368 mm, the 4-year MAI was 15.8 m^3/ha. Thus irrigation that raised water applications, including rainfall, to 970–1290 mm/growing season over 4 years doubled volume growth (Karschon 1970). In a rate-of-irrigation trial in the same area, the optimum regime, under which 1350 mm of water was supplied per season in addition to 600 mm of rainfall, the 4-year MAIs of two clones of *Populus deltoides* were 24 and 39 m^3/ha.

Table 5. Production of *Dalbergia sissoo* in irrigated plantations in the Indus Valley

Quality class	Age (years)	Mean annual increment[a] (solid m^3/ha)
1	10	5.9
	15	8.2
	20	10.1
2	10	4.2
	15	5.7
	20	7.6
3	10	3.1
	15	4.2
	20	5.0

Source: Troup (1921).
[a] Includes brushwood less than 2.5 cm in diameter.

Kuwait

Wood and Synott (1978) designed high-intensity forest production, environmental-protection forestry, and shelterbelt plantings, some of them widely spaced, to be grown under irrigation with sewage effluent near the city of Kuwait. *Eucalyptus camaldulensis* was to be a major species. Based on assessments of earlier plantings in the vicinity, e.g., those reported by Firmin (1971) and under comparable conditions elsewhere, they predicted that the MAI for this species at 10 years would approximate the equivalent of 25 m^3/ha for fully stocked stands.

Pakistan

Troup (1921) recorded MAIs for *D. sissoo* in irrigated plantations in the Indus Valley (Table 5). In a more recent report Lerche and Khan (1967) reported that the average MAI for marketable wood averages 2.5 m^3/ha for the same species in the same area, indicating that many aspects of management require modification and improvements to increase production some 3.5 times to the potential of about 9 m^3/ha per year. Even this does not appear to reflect the capability of the area, at least in areas unaffected by salinity, because other elements of the total biomass produced, such as twigs and foliage, are usually saleable as fodder or light fuel. Local yield tables usually ignore all material smaller than about 8 cm in diameter and are therefore not applicable for the management of intensively utilized plantations, which most of them are.

Dalbergia sissoo and *A. nilotica* are valuable, traditionally grown species in the area and will always be important. However, other species, e.g., poplars and *Eucalyptus* species, are capable of yielding greater volumes. Pryor was quoted by Lerche and Khan (1967) as saying that *Eucalyptus* species should produce an average of at least 18 m^3/ha per year in the area, and this is supported by the indications from small stands and trials.

Africa

Niger

On regularly flooded river-basin soils near Goudel, the total volume (outside bark) MAIs at 5.5 years were 31.6 m^3/ha for an *E. camaldulensis* trial and 42.6 m^3/ha for *Eucalyptus resinifera*. At Karma, under an irrigation regime of 270 mm of water from October to May to augment a mean annual rainfall of 550 mm, MAIs in an

E. camaldulensis provenance trial after 3 years ranged from 7.8 to 20.0 m^3/ha. In an unreplicated test of irrigation rates of 0, 270, and 460 mm/season, MAIs for the same species at 3 years were 4.6, 12.1, and 12.9 m^3/ha, the trees receiving the second and third rates clearly having reached the water table. In a flood irrigated spacing trial, again of *E. camaldulensis*, MAIs at 2 years ranged from 16 m^3/ha for a spacing of 3 × 3 m to 38 m^3/ha for 1 × 1 m (Hamel 1985). Jean Gorse (World Bank, Washington, DC, USA, personal communication, 1984) believes that well designed and conducted irrigated *Eucalyptus* plantations in the area would produce an average of 15–20 m^3/ha per year.

Nigeria

A provenance trial of *E. camaldulensis* was planted on lacustrine sands in the extreme northeast corner of Nigeria near Lake Chad and irrigated by sprinkler during the 1st year until the tree root systems were able to draw on underground water. The early growth, particularly of the 'Petford' and 'Katherine' provenances, was remarkable. Pryor (1970) stated that the 10 cm DBH and 11 m height attained by 17 months represented the most rapid growth for *Eucalyptus* recorded anywhere. Allan (1977) and Jackson (1976) reported that the MAI by 4 years of the fastest growing provenance was 21.8 m^3/ha. This clearly represented a falloff in growth after the 17-month measurement and is accounted for by the fact that irrigation was used only until the tree roots reached the water table.

Sudan

Masson and Osman (1963) gave the average yield of irrigated *E. microtheca* plantations in the Gezira as 7.3 m^3/ha per year at 7.5 years. In his analysis of production and production prospects for these plantations, Foggie (1967) noted that water was commonly applied irregularly and frequently in inadequate quantities. Under these conditions, the average yield was 6.6 m^3/ha per year although, sometimes, under more consistent watering regimes, MAI reached 9.9 m^3/ha per year. He believed that, under more adequate, regular irrigation, the average should be at least 12 m^3/ha per year. Ahmed (nd), in his management tables for the same species at Gezira, showed average MAIs from seedling stands at 9 years of 23.3, 14.1, and 6.9 m^3/ha for quality class I, II, and III sites with mean heights of 40–60, 40, and 30–40 m respectively. Ahmed also noted that MAIs in succeeding coppice rotations should average 15% more than those from the seedling rotations in class I sites and 10% more for class II stands, although it would be 17% less in class III stands. Ali (1979) confirmed Ahmed's predictions and indicated the scope for increases through improved management. He commented on the apparently anomalous yield prediction for class III coppice stands and suggested that the underlying silvicultural explanation should be sought.

Foggie (1967) recorded the MAI of the natural woodland in the vicinity of the Gezira plantations, without irrigation, as being about 0.5–0 6 m^3/ha per year.

Zimbabwe

In a carefully compiled and interpreted analysis of growth data, Barrett and Woodvine (1971) reported 4–6 year results from 138 unreplicated, usually small, trial plots covering 45 species of 13 genera under irrigation in Zimbabwe's silvicultural zone V — a semi-arid zone with annual average summer rainfall of 450–635 mm, three cool months, and hot to very hot summers — where growth rates of the natural woodland are 0.50–0.75 m^3/ha per year. Various irrigation and lateral seepage-water

Table 6. Representative rates of growth in irrigated trials in Zimbabwe.

Species	Age (years/months)	Mean annual increment (m^3/ha per year)
Acrocarpus fraxinifolius	5/8	7.1–8.3
Casuarina cunninghamii	4/11	6.6–12.5
Eucalyptus camaldulensis	5/8	14.9–65.5
Eucalyptus citriodora	5/7	6.9–26.8
Eucalyptus cladocalyx	5/8	7.3–18.3
Eucalyptus cloeziana	5/8	26.4
Eucalyptus crebra	5/8	12.4–12.8
Eucalyptus gomphocephala	5/8	15.0–18.9
Eucalyptus grandis	5/8	20.7–47.4
Eucalyptus leptophleba	5/8	14.8
Eucalyptus maculata	5/8	19.0–19.4
Eucalyptus paniculata	5/8	15.0
Eucalyptus punctata	5/8	18.8–28.9
Eucalyptus resinifera	5/8	21.6–41.7
Eucalyptus tereticornis	5/8	16.6–40.8
Eucalyptus tesselaris	4/8	14.4
Eucalyptus torelliana	4/8	17.6
Gmelina arborea	4/11	10.8
Grevillea robusta	5/8	16.1
Populus deltoides	5/1	14.5
Tectona grandis	4/11	8.5
Tectona grandis	7/9	14.8

Source: Barrett and Woodvine (1971).

situations were used as test sites. They were grouped into six types of regime, some of which changed during the trial period so that the plots affected were subjected to some degree of moisture stress. With the data for plots affected in this way excluded, Table 6 gives the plot MAIs at the ages shown for the more promising species.

These yields were achieved under irrigation conditions that can best be described as opportunistic — on the fringes of and along canals within areas of irrigated sugarcane and citrus. They do not necessarily represent production under optimum irrigated plantation conditions but equally, as noted, results for moisture-stressed plots have been excluded. The natural woodland that formerly covered the area largely comprised open stands dominated by *Combretum* and *Acacia* species with *Colophospermum mopane* and occasional *Adansonia digitata*. The average overall rate of growth of these species would have been of the order of 0.6–0.75 m^3/ha per year.

General

This short review of growth and yields under irrigated conditions may be concluded by noting three points.

- The published information on growth and yields is meagre. Although unpublished information is undoubtedly available in some countries, this is clearly a priority topic for research.
- The growth and yield data available in all cases, except the data of Troup (1921) for *D. sissoo* in the Indus Valley, exclude at least smaller branches, twigs, and foliage. These excluded elements would, in most cases, amount to an additional 20–30% of the volumes shown. Extension of existing volume and yield tables to include these elements of production is another priority research topic.

- In all instances, comparable yields without irrigation would be those from the natural woodland that formerly occupied the sites of irrigated plantations, i.e., as noted in the sections dealing with Sudan and Zimbabwe, 0.50–0.75 m^3/ha per year.

Research Needs

Reviewing the literature on irrigation, particularly of forest trees, leads to the general impression that the topic unquestionably requiring most and most-urgent elucidation by research is that of the water requirements and responses of plants grown under irrigation in relation to different stages in their development, different forms of plantations, and different environmental (including soil) conditions: not simply the ideal but also how much water would sustain a practically acceptable response, and when and how often to apply it. This need is confirmed by specialists concerned with plantation irrigation in areas as diverse as Mali (IBRD 1979a), the United Arab Emirates (Satchell 1978), Niger (Delwaulle 1979 and others), Pakistan (Ahmad 1975; M.I. Sheikh, Pakistan Forest Institute, Peshawar, Pakistan, personal communication, 1984), and Iraq (Raeder-Riotzsch 1965). Information on this topic is required for the formulation of efficient regimes of irrigation amounts and frequencies in the interests of optimal production (NAS 1974), economy in the use of water (Van der Zel and Wicht 1974), preservation of site fertility, and minimization of drainage requirements and costs, including those for disposal of excess water. Such results, which would not necessarily be transferable without testing at the new site, would be valuable because of their general applicability over a wide range of conditions, as well as at the local level.

Although the question of the water requirements of crop species is likely to continue to be the one of primary concern in adaptive research, as discussed earlier in this chapter, there is a dearth of established rules and principles to guide water application aspects in the design of irrigation systems for tree species. In this respect, the published results of work by Karschon (1970) and Rawitz et al. (1966) represent examples of what is required. Although the studies described by Raeder-Riotzsch and Masrur (1968) in Pakistan and Chaturvedi et al. (1984) in India mentioned in chapter 3 concern young seedlings, they illustrate effective research contributing to the determination of field watering regimes.

Tunisian work reviewed by Van Hoorn et al. (1968) indicates the extent of success that can be achieved through research to develop methods of irrigation in which water of marginal quality, in this instance, brackish water, is used. This research, which began in 1935, resulted in the determination of the limits of salt tolerance of plants (mainly, but not exclusively, annuals); methods, rates, and frequencies of application of water; and drainage systems in successful irrigation schemes in which trees were included. As mentioned earlier, work of this nature (although of a more empirical nature) is in progress in other desert and semi-desert areas such as Kuwait and Abu Dhabi. It may be expected that the need for development of methods for such difficult situations will increase. Also, it is likely to do so in connection with the reclamation and use for wood production of areas that have become charged with salts as a result of seepage or excessive irrigation, or both. Thus, methods of reclamation must be developed, particularly those appropriate for use after basic reclamation by pumping and disposal of the excess water and leaching have begun.

As noted earlier in this chapter, Doneen (1972) gives guidelines for experimental design for research on plant water requirements. Although focused primarily on annual crops, these guidelines could be adapted readily to investigations with tree crops. Personnel concerned with the supervision of a World Bank-supported forest-plantation irrigation project in Mali recommended that, where there is difficulty in forecasting the performance of trees under irrigation, it would be wise strategy to undertake preliminary, empirical, small-scale trials in advance of initiating a major program. The research described by Barrett and Woodvine (1971) is a good example of the approach that would be appropriate, although the design would have to include irrigation rates and frequencies as variables to be studied, as well as replication.

Almost as frequently recommended in the literature as an important topic of research in relation to irrigated plantation developments is that of testing, selecting, and breeding varieties that are particularly well adapted to such cultural treatment, including salt-tolerant species, provenances, and cultivars. The need is mentioned by Edgar and Stewart (1979), Barbier (1978), and NAS (1974), among others. That provenance variation clearly also exists in relation to irrigated culture is shown by trials with *Eucalyptus* species, for example, in Niger (Barbier 1968 and others), at Mallam Fattori in Nigeria (Pryor 1970) and the Gezira plantations (FAO 1969). As noted in chapter 6, Dickmann (1975) suggests the use of a hypothetical ideotype as a useful means of goal-setting in breeding work aimed at producing types suitable for the production of specific kinds of wood under intensive irrigated plantation schemes. In the irrigated tree plantation trials in Zimbabwe, assessment included scoring of individual stems for straightness. In addition, the presence or absence of flowering and fruiting was recorded at each assessment. These data were collected because of their value when it comes to selecting provenances or phenotypes in tree-improvement programs and in the development of seed-production arrangements. As mentioned in chapter 6, large gene pools, e.g., of genera in the Casuarinaceae, await exploitation through species and provenance trials leading to more intensive selection and breeding.

Research is required to determine optimal fertilizer regimes to be applied under specific irrigated conditions.

Silvicultural regimes and rates of production per unit area and length of rotation by tree species are usually remarkably variable in any particular locality. This reflects variability of cultural treatment including irrigation regimes, as much as anything else. Much of the scope for correcting this feature lies in the field of project management and supervision. However, it also calls attention to the need, generally as well as locally, for the refinement of irrigation systems, the testing of ranges of silvicultural regimes, and the production of operational guidelines based on research development in these subject areas. This will necessitate research to develop silvicultural design and treatment methods suitable for application under irrigation, including the integration of trees with agricultural production.

Tree–annual crop designs for use at the level of the individual farmer require further development, as do related tree-management and harvesting techniques, such as coppicing, pollarding, and lopping. Design and silvicultural management research for agroforestry would entail a strong focus on tree–agricultural crop interactions and on methods to minimize or optimize them. Research is also required into methods of plantation establishment and management in waterlogged, saline areas.

There is a need for much more informative tools for plantation management (e.g., site index and yield tables) than are usually available, even after many years of

irrigation practice. This calls for growth and yield research and the use of the data to produce growth models that can be used by planners and project managers. Tables for yield prediction should relate to total biomass production (classifiable into various assortments) under different silvicultural management systems and methods. Most existing volume, yield, and assortment tables relate only to timber and large pole dimensions; they could readily be extended to reflect total wood as well as forage yields.

Where municipal and industrial wastes are used for irrigating tree crops, research must be undertaken to gauge the fate of the dissolved and suspended elements and compounds carried in this water, their short- and long-term effects on the nature and production of the soil and on groundwater, and the effects on tree growth of variations in the effluents (Edgar and Stewart 1979). Such research is particularly needed where there could be any question of indirect effects on the health of humans or animals or on long-term site productivity.

There are frequent pleas in the literature for economics research in relation to irrigated forest plantations. This is taken to mean that the need is for more frequent economic analysis of projects of this sort. This would call, in turn, for better information about plantation systems and yields as well as costs in relation to well defined environmental and social conditions. Such needs postulate challenges in respect of both data collection and production as functions of project management, and research to provide a good basis for them.

In conclusion, it may be noted that research activity in relation to plantation irrigation may take one or more of three general forms:

- Basic research aimed at establishing new principles on which to base innovative technology development;
- Research development aimed at applying established principles and new concepts to develop new irrigation or plantation methods, or to find new and better tree species, provenances, land races, or cultivars; and
- Applied research to test, refine, or improve the systems and methodologies being practiced.

In irrigated plantation projects, the last of these three kinds of research would be the most commonly practiced: an enterprise could hardly succeed and progress without supportive work of this kind on a continuing basis. The second type of research activity would be less common, although usually necessary and important in the early phases of project development. The need for basic research, which is often long-term and costly, would arise only occasionally. When it does, it should be linked in appropriate ways from the beginning to the field phases it is intended to support.

9. Economics of Irrigated Plantations

Needs, Opportunities, and the Need for Evaluation

Irrigated tree plantation projects vary in scale and scope. They can take the form of a few trees planted by individual farmers in an agroforestry setting along roads, irrigation channels, or field boundaries or in small areas of otherwise unused ground. In such cases, the water usually becomes available, through seepage or reuse, as a result of the primary activity of irrigated agriculture. A series of such individual initiatives in a locality might be coordinated into a program of shelterbelt development to enhance the overall benefits. An individual farmer, company, or corporation might grow plantations as a primary activity or the plantations might be grown by a local, regional, or national government. The initiatives might come about as the result of opportunities for beneficial use of wastewater, e.g., municipal or industrial effluents.

In all cases, the tree-growing enterprise would be undertaken in response to some expected need. This might be domestic fuel, bean sticks, building poles, fencing materials, or fodder to meet the needs of the family concerned. At the level of the individual farmer, indirect benefits would result from substitution for the commodities previously used, e.g., replacement of kerosene or coal as domestic fuel, the dung previously used as fuel might now be used as manure, or the expense of purchasing building or packaging materials or fodder would be avoided. Tree products, including surpluses after the needs of the family have been met, might be sold to enhance farm income. There would also be less tangible benefits, such as the greater convenience of producing needed commodities in the vicinity, savings of time that would otherwise be spent in carrying fuelwood from distant sources, beneficial shelterbelt influences, the benefits of shade to the household and its stock, esthetic values, and enhancement of the quality of life. The tasks involved in establishing and managing the small-farm tree crop need not seriously compete for time with the principal preoccupation of agriculture because irrigation introduces a degree of flexibility in the timing of tasks that would otherwise be seasonal. This ability to undertake irrigated forest plantation work with flexibility as to timing has the added implication that, where such enterprise becomes an additional means of employment, such new work opportunities will usually occur in the off-season for agriculture.

Larger irrigated plantation enterprises financed by governments or companies may be undertaken to meet the needs for fuelwood, poles, and sawlogs, and environmental influence on rural or urban communities. They generate direct, indirect, and intangible benefits similar to those of farm-forestry although their scale, costs, and complexity are greater. Such enterprises are often linked, at least to the extent of having a common water supply, with agricultural projects.

All instances of irrigated plantation development, of whatever scale and however critical the need for the products, are subject at some stage to some form of economic

Irrigated tree plantations take many forms including single- or multiple-row shelterbelts in agricultural fields. A Casuarina *belt along the edge of an irrigated rice field in Burkina Faso — in this instance, growth of the rice appears to be unaffected.*

analysis as a means of assessing the feasibility of the development in the first place, the merits and drawbacks of alternative strategies that might be used, including technical methods and monitoring procedures. The individual farmer concerned with integrating a few trees into the farm's operation would consider feasibility by comparing the inputs of time and other resources that would have to be made with the benefits that can be expected. The larger and therefore the more complex the enterprise, the more complex and formal the analysis would be. In either case, however attractive an enterprise might appear to be in prospect, not to undertake such analysis before committing resources to it, and at intervals thereafter, is to court a suboptimal outcome. Methods of economic analysis for these purposes are outlined in the balance of this chapter with references to some of the projects discussed in earlier chapters.

Economic Analysis and Evaluation

At the beginning of this section, a few cases are briefly outlined. These are generalized preliminary or prefeasibility analyses leading up to the identification of needs or opportunities for irrigated plantation developments that appear to warrant analysis in depth. This is followed by an outline of the economic analytical methods commonly used for the analysis and for comparison of alternative projects — some actual cases are referred to briefly. Finally, the application of some of these methods in the review of three existing projects — Gezira and Indus Plains irrigated plantations and the irrigated species trials in Zimbabwe — is discussed.

Preliminary assessments to identify feasible projects for development of irrigated plantations are made on the basis of somewhat generalized analysis, usually based on limited data augmented by reasonable assumptions. They may be followed by one or

more further studies of major features before the potential for development is confirmed. Generalized assessments are also sometimes made of existing projects to identify aspects requiring detailed analysis as a prelude to introducing modifications in an informed manner. Thereafter, rigorous analyses are undertaken using additional data from surveys done for the purpose, leading to the selection of the most appropriate design alternatives. When shortcuts are taken, either before or during the design phase, confused, unsuccessful development can result.

Several examples of preliminary assessments of these types can be mentioned. Thus, on the grounds of general indications of the needs for fuelwood and building materials, of concentrations of population, and of the biological possibilities once the necessary water supplies were assured, Ferlin (1977) saw a definite role for irrigated forestry plantations in the Sahelian zone, where he believed that their profitability would be certain. Pryor (1953) noted that plantations were competing successfully with agriculture in irrigated areas in Iraq. He implied a degree of deprecation of this trend but observed that there was a tendency to use the poorer areas for forestry. This was justified in any case by the acute demand for wood and for shelterbelt effects in the agricultural areas. Adverse sociological comment on substitution of tree cash crops for labour-intensive food growing has also been made in Gujarat and Karnataka. Veltcamp (nd) noted that fast-grown poplars compete favourably with agricultural crops, including vegetables, in the Jordan Valley and could be expected to do so to a greater degree as sites used for the latter deteriorate under the very intensive irrigated agricultural practices used.

Foggie (1967) undertook a classical analysis of existing plantations and other wood resources in the Gezira area of the Sudan to determine the requirements of the population of the area for forest products; to estimate the additional area that should be afforested; to initiate measures to develop methods of plantation production (including irrigation regimes), management, harvesting, and marketing; to initiate studies of the role of shelterbelts and their effects on agricultural yields in the Gezira; and to recommend appropriate action in this respect. The study area covered about 27 000 km^2 with a population of 1.65 million, which was forecast to rise to 1.9 million in 1971 and 2.6 million in 1981. The area had been acutely short of forest products for some 45 years. The area of irrigable land potentially available to meet the wood needs of this population represented 0.39% of the area of the Gezira project, including 3700 ha (0.14% of the area) already under plantations that produced 3% of current demand. It was recommended that the area of plantations in the expanding agricultural irrigation areas should be increased to 69 300 ha and that tenant farmers should participate in this increase. These plantations would meet 26% of the wood needs of the future population. It was proposed that the remainder should be met by reservation and management of 1.47 million ha of savanna woodlands to the southeast and south and across the White Nile to the southwest and west.

Foggie reviewed plantation practices and recommended better leveling of plantation sites as well as generally higher and more regular irrigation rates pending the outcome of a range of research development studies that he proposed for the improvement of plantation establishment and management. Foggie's analysis in 1966–67, for which the data were often meagre, indicated that the plantations were not showing a profit because of delays in some operations, a conservative selling policy, and sales at subsidized rates as well as inadequate site preparation and irrigation. He felt that if these factors were corrected, the enterprise would definitely show a return of at least 10% on the capital invested.

Foggie's plantation extension targets have never been met. However, all the subsequently reported studies in relation to irrigated plantations in the Sudan stem from his recommendations.

In his review of fuelwood plantation development along the Nile at Shendi in the Sudan, Wood (1977) noted that, bearing in mind the high prices for fuelwood, there were indications that irrigated plantations could pay. He pointed to a number of changes that were needed in the development approaches used and emphasized the need to keep good cost records.

Both economic and financial analysis depend upon the availability of reliable, complete data on costs and benefits, including physical inputs and outputs, i.e., labour, quantities of water, volumes of wood, etc. They should be generated routinely as part of the management process. There should be no difficulty about this because it is a straightforward matter. That there sometimes is difficulty, however, is shown by some of the observations of Wood (1977) in respect of plantation irrigation projects on the Nile near Shendi. For developments being considered for the future, best estimates must be used, based on situations as nearly comparable as possible or on research undertaken to quantify variables (Mace and Gregerson 1975). Approaches to and formats for compiling data on costs and benefits for management and accounting purposes are discussed by France (1977), Openshaw (1980), and Sagardoy et al. (1982).

Methods of economic analysis for comparing alternative projects, or alternative components of projects, to determine which to accept and which to reject are described by Gittinger (1982). His account focuses on agricultural projects, including irrigation projects, and is applicable to irrigated forestry plantations. It forms the basis for the outline that follows, which is included here because documentation of the methodologies is not always available to field technicians and managers.

The objectives of an analysis provide the standards for defining costs and benefits, which may simply be done by recognizing anything that reduces income as a cost and anything that increases it as a benefit. Costs may be tangible (e.g., physical goods, services, labour, land, and contingency allowances) and so may benefits (yields, increased production, and quality improvement). Costs and benefits may be secondary, but because secondary costs and benefits are external to the project, they are not usually taken into account in financial analysis. However, the fact that they usually are taken into account in economic analysis is the principal feature that distinguishes economic from financial analyses. Thus, a secondary or indirect benefit of an irrigated plantation project to produce fuelwood for a city might be that it would take the pressure for this commodity off the remaining area of depleted natural woodlands, thus saving them from extinction. This would be taken into account in an economic analysis but not in a financial one. In economic analyses, secondary costs and benefits are taken into account by adjusting the tangible values used rather than by attempting to bring them in separately. Intangible costs, e.g., waterlogging and salinization, are not common; intangible benefits are more usual features, examples being creation of employment opportunities and recreation benefits. In both cases, valuation in quantified terms is difficult and the usual course adopted is to identify them, quantify them in appropriate terms, but not to value them in monetary terms.

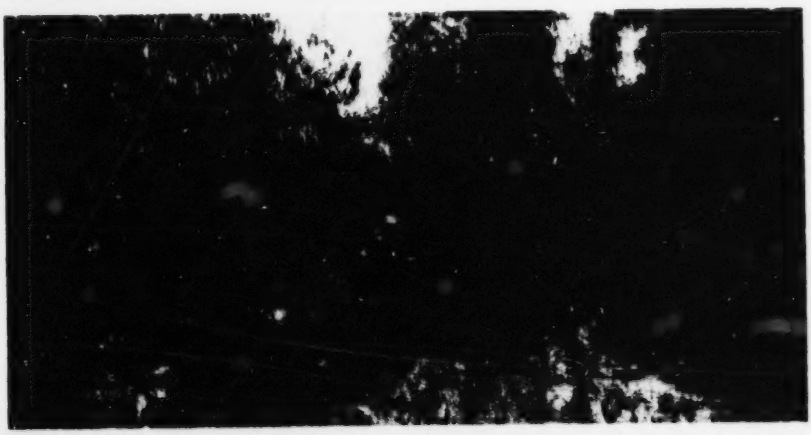
Once all the costs and benefits have been identified, priced, and valued in economic terms (e.g., by taking into account transfer payments and price distortions), they can be compared to determine which alternative to accept and which to reject. In

some cases, it might be possible to do this by straightforward inspection of the costs and benefits information and selection of the alternative that is clearly the best. However, particularly in projects lasting several years and involving perennial crops, the alternatives may have differently shaped cost and benefit streams or they may be of different sizes or span different time periods. This makes selection based on simple inspection difficult or impossible. Recourse is then had to techniques that take account of the effect of time on the value of money by discounting the costs and benefits and thus reducing them to comparable net present values. Four discounted measures have been found to be suitable for the analysis of agricultural, including irrigation, projects: net present worth (NPW); internal rate of return (IRR); net benefit investment (N/K ratio); and benefit–cost ratio (B/C ratio).

The basic arithmetic of these four discounted measures, the way they are interpreted, and their limitations are similar whether they are applied to economic or financial analysis. In the former, however, economic values are used whereas the latter is concerned with financial prices. It is important to bear in mind that these techniques — none of which is the "one best" technique for estimating project worth — are used to sharpen comparisons and thus improve decision-making: they are not a substitute for judgment.

In the first three measures, costs are subtracted from benefits year by year to arrive at the incremental net benefit stream, or cash flow, and then to discount that. In the benefit–cost ratio method, the present worths of the benefit and cost streams are found separately and the ratio between the two is then calculated. Because the two streams, benefits and costs, are discounted separately rather than subtracted from one another year by year, the benefit–cost ratio is not a discounted cash flow technique. Before considering the derivation of those measures and features that influence their use, it is necessary to consider the alternatives for selecting the discount rate to be used.

The discount rate applied in financial analysis is usually known as the cut-off rate, i.e., the rate below which it would be unacceptable for the internal rate of return to fall. This is taken to be equal to the marginal rate of borrowing money. In practice, it is usually the rate at which money can be borrowed.



Tree growth in arid areas is markedly sensitive to the overall availability of moisture as well as to the frequency and amounts of water applied. Eucalyptus camaldulensis *plantation in Tahrir Province, Egypt — note difference in growth between irrigated (right back) and nonirrigated trees (left front).*

In economic analysis, one of three alternative discounting rates is used. The first is the opportunity cost of capital, which is somewhat theoretical, difficult to ascertain precisely, and difficult to apply as a practical working tool, but usually considered in the developing world to be between 8 and 15% in real terms — 12% is usually used in practice. The second alternative rate is the borrowing rate to the country, which is influenced by the financial terms available for borrowing money and not solely by the potential relative contribution of the project to the national economy; if two sources of loan funds are available at different rates of interest, the average rate is used. The third rate that can be used is the social time preference rate, which is sometimes preferred because it reflects the worth of the project to society as a whole and not simply to an individual (in which case it would be a higher rate).

In deriving the incremental net benefit stream or cash flow for the first three discounted measures, capital investment and operating costs are deducted from the benefits year by year. The difference, or residual, is the net benefit stream (which differs from profit because depreciation is not taken into account). Return of capital is allowed for by discounting each year's residual before carrying it forward to the next. In economic analysis, duties and taxes are not deducted as costs when deriving incremental net benefit streams whereas in financial analysis they are. For the early years of a project, before yields accrue on any substantial scale, the incremental net benefit is usually negative.

Net present worth (NPW) is the most straightforward measure of project worth. It is the present worth of the incremental net benefit, or incremental cash flow, stream. As with IRR and the N/K ratio, it has the practical advantage that netting out is done at each annual, or any, point in the calculation — this is not the case with the B/C ratio.

The internal rate of return (IRR) is the maximum rate of interest that a project could pay while repaying its investment and operating costs, and still break even. It is used as a measure by the World Bank and many other international institutions. When used in financial analysis, it is known as the financial rate of return whereas it is called the economic rate of return in economic analysis. It is most important to note that, when considering mutually exclusive projects, direct comparisons of IRRs can lead to erroneous investment choices; in such cases, the NPW criterion should be used. The IRR indicates the rate of return of a project to national income relative to the resources used; thus it can be used for ranking projects only in a very general way.

The net benefit investment (N/K) ratio is the ratio between the present worth of net benefits and the present worth of the investment. More clearly, it might be described as being the sum of present worths after the incremental net benefit stream has become positive divided by the sum of present worths in the earlier years of the project.

The N/K ratio is a convenient criterion for ranking independent (i.e., not mutually exclusive) projects. Its value lies in this feature because none of the other three can be used in this way. In them, all projects are selected that meet the criteria of having an NPW of zero or better at the opportunity cost of capital, an IRR equal to or greater than the opportunity cost of capital, or a B/C ratio greater than unity at the opportunity cost of capital. The IRR and B/C ratio are commonly used but they have limitations that make the N/K ratio preferable in many instances.

The B/C ratio is a discounted measure of project worth. However, because the cost and benefit streams are discounted separately and not subtracted from one another year by year, it does not represent a cash flow. It is not usually used as a criterion for

projects in developing countries because the value of the ratio can change markedly depending on where the netting out occurs. As might be expected, the ratio diminishes as the rate of interest used increases. As already noted, the use of the B/C ratio in comparing mutually exclusive projects can lead to erroneous choices, a danger that is avoided when NPW is used. An advantage of the B/C ratio is that it can be used to gauge how much costs could rise before a project becomes economically unattractive. The amount by which an element of a project can change before this point is reached is known as the switching value. Although projects with higher B/C ratios are usually considered preferable to those with lower ones, ranking by this criterion can result in erroneous choices because it discriminates against those with relatively high gross returns and operating costs, even though these may have a higher wealth-generating worth.

Gittinger (1982) illustrates the use of the foregoing techniques for selecting among project alternatives by applying them to four hypothetical alternatives for irrigation pumping investments. Pillsbury (1968) gives guidelines for similar analysis in respect of sprinkler irrigation equipment alternatives.

It is pertinent to end this outline of analytical techniques for selection among project alternatives by noting what Gittinger (1982) saw as major problems of project design and implementation after reviewing a large number of World Bank projects. They are inappropriate technology, inadequate infrastructure and support systems (including extension services, training, and the like), failure to appreciate the social environments of projects, and problems due to weak management and administration. Important reasons for poor project analysis were listed as poor analysis (sic), underestimated costs, excessively optimistic projections (forecasts), failure to appreciate the variability of climates and the effects of this, over optimistic timetables for project implementation and lack of appreciation of the implications of project actions, e.g., in some cases, the decision to line preexisting canals to prevent seepage would put existing wells dependent on that seepage out of action.

A good example of the use of economic analysis methods to gauge the increase and relative strengths and weaknesses of irrigated forest plantation projects was the wide ranging assessment of government irrigated plantations of the Indus Basin in Pakistan by Lerche and Khan (1967), who were hampered in their task, however, by inadequacy of the records, particularly of yields. After an encapsulation of the history of the activity since its inception in 1864, the plantation management system was reviewed critically in relation to the objectives of the projects, particularly with respect to site preparation, the elaborate system of trench irrigation in use, species selection, and irrigation and silvicultural regimes and rotations. Assuming a rate of interest of 5%, average investment, operating, staff, harvesting, and marketing costs were reduced to current values on a per-acre of plantation basis and set against average yields and their assortments valued at average selling prices to indicate the average net return per acre. Comparable results were estimated for alternative, more productive stand spacing regimes, lengths of rotation, irrigation scheduling, and species. They indicated the order of magnitude of greater favourability of results that could be achieved with major changes in management. It was concluded that, if these were introduced, the enterprise would compare favourably with rice and sugarcane production even if the preferential charges for water enjoyed by forestry did not apply. At the higher rate, other forms of agricultural production would be economically more attractive. The analysis was positive and valuable in providing insights and the basis for a series of recommendations for changes to the types of material to be produced and the species and silvicultural, irrigation, and management methods for doing so.

An appraisal of the Gezira plantations in the Sudan by Ali (1979) is another example of the application of economic analysis techniques to irrigated forest plantation activities. The net discounted present worth approach was used to compare the present regime of growing *Eucalyptus microtheca* on an 8-year seedling plus two 7-year coppice rotations with the seedling rotation of maximum volume production (8 or 9 years depending on site index); to determine whether to regenerate the plantations by coppice or to replant at the end of the seedling rotation; and to determine for each of three site classes the rotation of maximum economic benefit when coppicing is not practiced. Early in the analysis, it became apparent that there seemed to be no justification for the belief that coppicing is economically preferable to planting at the end of the seedling rotation unless the value of the shelterbelt effect of the forest crop, which would be lost during the short period of regeneration by replanting, was brought into the equation. This unexpected and anomalous result (regrowth in the first coppice rotation is usually 10–15% more rapid than seedling growth) led the analyst to recommend silvicultural study to ascertain the reason for this finding. Subject to whatever might be the outcome of such study, and after applying the NPW and B/C ratio criteria in financial and economic analysis, it was concluded that, in general, a higher return would be derived from an 8-year seedling rotation on quality I sites or 9-year rotations on quality II and III sites than from one seedling and two subsequent coppice rotations in each case. Financial analysis gave slightly more favourable results for coppicing than when economic values were used. Mean annual increments (already quoted in chapter 8 under the heading " Growth and yields") were given for optimum seedling and coppice rotations on sites of the three qualities. Other conclusions from the analysis concerned the desirability for greater regularity in the irrigation regimes applied (which, as was noted in chapter 8, was confirmed) and greater discrimination in the selection of plantation areas to exclude those that are oversaturated with water or affected by salt.

The value of the irrigated tree species trials in the low veld of southeastern Zimbabwe, described by Barrett and Woodvine (1971), was enhanced by a concise economic analysis by P.F. Banks: it gave the trials and their results a meaningful regional perspective. Production from such plantations grown on a 5–7 year rotation were compared on the basis of discounted present costs and values with that from the best plantations grown on similar rotations in the high-elevation, high-rainfall plantation areas usually used in an adjacent region for the production of industrial wood. The analysis was done for alternative discount rates of 6, 10, and 15%. It indicated that the somewhat higher cost of production under irrigation in the semi-arid lower elevation area was easily offset by the superior value of the increased production achieved, compared with that at higher elevation, higher rainfall sites.

10. Organization and Management

It has frequently become a matter of concern that, in relation to their high cost, the performance of many irrigation schemes has fallen well short of expectations. This is not only a consequence of technical design deficiencies; many of the problems result from weak organization and management, compounded in many cases by inadequately vigorous analysis and measures to rectify the causes. Successful schemes result from good management at all levels — the individual grower, the project within which he operates, and responsible organizations at the basin, watershed, or national level. It is at the second of these three levels, the project, that management is most frequently inadequate and overlooked in attempts to make improvements, presumably because, being concerned with the management of the whole system, it is the most complex level, the higher ones being involved in more general phases whereas the lower one, although technically important, is narrower in scope and technical complexity and therefore more susceptible to being properly organized.

Project management is effected through a series of suitably staffed, coordinated units, each of which is responsible for a set of specific activities. The manner in which the multiplicity of functions to be carried out is grouped will depend on the size, nature, and specific circumstances pertaining to the individual project. They may be considered broadly as being concerned with project operations, extension, maintenance, and administration and financial services.

The principal functions of an operations service would be

- Planning the operations, i.e., activating water supply, assessing crop water-demand patterns and amounts, and matching supply with demand;
- Distribution of water according to the methods in use;
- Establishment and management of the tree crop, where this is not the function of individual landholders;
- Extension services; and
- Short- and long-term monitoring of these operations.

The primary responsibilities of the maintenance service would be to plan in detail, implement, and monitor the maintenance of reservoirs, canals, and other distribution channels, pipelines, and devices and the drainage network, including the ancillary equipment for these. The responsibilities of this service might also include the maintenance of roads, buildings, and transport and general equipment. If it does, care should be taken not to permit these tasks to confuse or frustrate the primary function.

The administration service would be responsible to the project manager for accounting, personnel, legal and general administration matters, and supply and procurement.

The basic requirements for effective management are an appropriate organizational structure, the application of suitable management methods based on a sharply analytical approach tempered by realism, and the provision of technically adequate services. Professional staff and technicians should receive formal training in organization and management: unfortunately, this need is all too often neglected in the training institutions that they attend. It is not surprising, therefore, that inadequacies of management and administration were among the problems of irrigation project implementation and operation identified by Gittinger (1982) and in the programs reviewed by Lerche and Khan (1967) and Ahmad (1975).

A comprehensive manual on the organization and management, operation, and maintenance of irrigation schemes was published by the French Ministry of Cooperation (France nd) and another by FAO (Sagardoy et al. 1982). These are valuable detailed references based on experience and analysis of irrigation projects of a wide range of sizes covering various institutional situations in many countries. Although focused on irrigated agriculture, the structures and functions described are equally applicable to irrigated forestry schemes, which may be associated if not actually integrated with agricultural projects. The two references form a major part of the basis for this outline.

Organizational structures are of two basic types, i.e., segregated or integrated. The former is based on the assumption that the overall production goal can be attained through the interaction of individual organizations acting independently, although in a coordinated manner, to achieve objectives such as efficient use of water, achievement of optimum production with the available input resources, and marketing the products to maximum benefit of the producer. Organizational structures of this type apply principally to agricultural irrigation schemes involving large numbers of farmers. They could apply to irrigated plantation schemes operating in the same way. However, they are prone to being flawed, particularly in respect of elements other than that responsible for water supply, and will not be considered further here. Integrated organizational structures comprise several coordinated, interacting units operating through a clear chain of command. When the project involves a number of individual land owners, as in settlement projects, care has to be taken to ensure that overlapping or conflicts do not take place in relation to preexisting arrangements for such functions as the supply of credit, extension services, and applied research. It is important that such structures should be well organized, technically equipped, and adequately funded, particularly at the project level, to which full authority should be delegated to enable operations to work smoothly.

Organizational structures have horizontal dimensions, relating to the rational differentiation of functions among separate but coordinated units, and a vertical dimension, that is, the manner in which responsibilities are assigned at different levels of the organization. The form of horizontal organization as well as the manner of distribution of responsibilities would depend on the level of economic development reached, the scale of the project, and also, very much, on the nature and character of the institutions concerned, i.e., whether the plantations are grown and managed by individual landholders or by a government organization or corporation, and the relative importance of irrigation in the local economy.

In large projects involving many individual growers, the organizational structure would include units concerned with water distribution, system maintenance, assessment and collection of water charges, extension and assistance with water use and growing and managing the tree crop, research development, infrastructure, and mar-

keting. The extent to which these functions are grouped, i.e., the degree of subdivision, will depend on the technical personnel available and the stage of development of the scheme. The organizational structure would evolve as the project passes from the planning to the implementation, transitional, and full development stages.

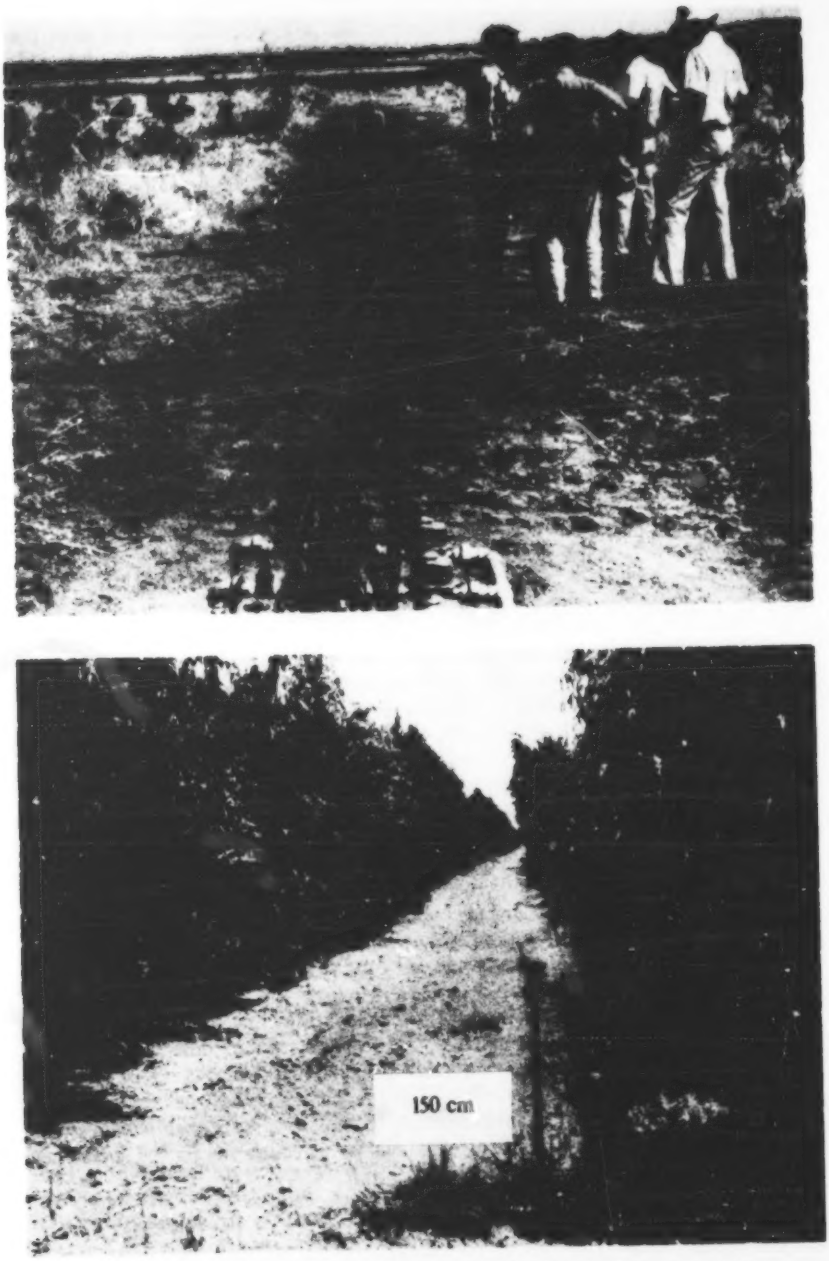
Smaller projects involving individual growers are often run by associations and small management groups representing the growers themselves with inputs and advice on managerial and technical matters from suitably qualified officials. Such organizations can be extremely effective although they need guidance in the formative phase. It is usually desirable to delegate as much responsibility as possible from government officials to the growers themselves. The extent of delegation would depend upon the level of education and irrigation experience of the latter. At the government level, it is important that maximum responsibility be delegated to the project manager and project staff so that they can perform their management and technical functions expeditiously.

In the field of irrigated agriculture, a range of types of irrigation organizations has developed that may be characterized according to whether responsibility for all the activities concerned (water management, extension, applied research, marketing, etc.) or only some of them are included in the organizational structures, and the degree to which management is controlled by the growers or government representatives. The various alternatives are relevant here because irrigated plantation activity is often an integral part, with agriculture, of the rural economy. The more important types of organization may be grouped as follows:

- Integrated management organizations having the characteristics already mentioned. Some organizations of this kind, usually termed service cooperatives, are run by growers themselves. Two others, i.e., state farms (large production units) or irrigation settlement projects (rural production units), are usually fully controlled by government officials.
- Specialized water-management organizations, i.e., social organizations, the function of which is timely and equitable water distribution among the growers of a community. The operational management units responsible for irrigation and drainage systems, maintenance, and collection of water charges are supported by service units responsible for finance, personnel, planning, and monitoring. Broad types of such organizations are those mainly controlled by the growers, e.g., irrigation associations, public irrigation schemes that are mainly controlled by government officials, and irrigation schemes with mixed control.
- Multipurpose water-management organizations that have responsibilities directly related to water management whereas separate units deal with such essential functions as extension, research, and marketing. This type of organization would be used, for example, where an integrated type of management organization would be unnecessarily complex or lead to duplication with existing institutions, whereas a specialized structure for water management would not provide sufficient service.

Individual countries tend to have their preferences for one, or sometimes more than one, of these types of institutions, the main characteristics of which are described by Sagardoy et al. (1982) with illustrative organization models.

One of the two principal functional phases of management of irrigation schemes is that concerned with the direction and coordination of decision-making within the



Localized irrigation (irrigation au goute-à-goute) adapted to conditions at a World Bank-financed project near Niamey, Niger: General view 4 months after planting showing buried lateral pipe along a cleared line with distributaries to plantation rows on each side (top) and view between two tree rows 20 months after planting (bottom).

project. Its purpose is to get all those involved to work toward the achievement of the objective of the project. The other relates to the functioning of technical, specialized activities such as water distribution, system maintenance, plantation silviculture and management, extension, and accounting. These functions call for particular kinds of management skills and styles of operation.

Project management is concerned with the implementation phase of the planning cycle (plan formulation, implementation, evaluation, and plan reformulation) and with budgeting, programing, and monitoring. The project manager is not simply an administrator who acts pragmatically as problems arise: one of his principal functions is to plan. His more important tasks include

- Setting objectives and priorities;
- Directing annual planning and budgeting;
- Directing the formulation of detailed work programs of the component project units and staff members within them;
- Monitoring and training staff and growers in the implementation of the program;
- Supervising the day-to-day implementation of the program and seeking solutions to problems that arise;
- Monitoring project performance against objectives;
- Monitoring staff performance against agreed work targets;
- Seeking opinions of growers about the quality of services provided by the project; and
- Identifying strengths and weaknesses and finding or proposing remedies for the latter. For this task, he or she will require a system for monitoring and identifying needs for strengthening or corrective measures in relation to three input areas: financial, personnel, and equipment resources; technical, management, and communication skills; and material and nonmaterial incentives for motivation.

Important requirements for effective project management, which should be given careful consideration in the project planning stage, are

- A well designed irrigation and forest management system;
- An appropriate organizational structure;
- The establishment of consistent, clearly defined objectives;
- A well designed project management system (management procedures, job descriptions, and information and monitoring systems);
- Defined policies on staff recruitment, production, and conditions of service that provide incentives for attainment of project objectives;
- Adequate financing to meet recurrent expenditure; and
- An effective legal framework for the enforcement of water distribution rules or control of groundwater extraction.

These requirements are ideal. In practice, the last three are often the most difficult to provide, for reasons outside the control of the project. They should, therefore, be matters of priority concern to, and under continuing active review and scrutiny by, the responsible senior officials of agencies controlling the project and its program resources. Problems created by the inadequacy of system design, including the design of the organization and management structure itself, can be the most serious obstacles to success.

Management guidelines are required for the performance of both the overall management function and the specialized activities. An example of a system that is

particularly relevant to the overall management function, the principles being applicable also to the specialized activities, is the "Programming and Implementation Management System" developed by Belshaw and Chambers (1973) for development programs in Kenya. It has three main components — a programing exercise, a management meeting, and an action report.

- A programing exercise is carried out annually just before or just after the beginning of the financial year, when all those concerned with implementation, including senior and junior managers and supervisors, jointly draw up a phased work program for the ensuing year. This lists the agreed operations to be carried out and the *names of those responsible for each*, start and completion times, and targets and completion indicators. The feasibility of each part of the program is checked and targets agreed and accepted by each member of the group.
- The management meeting is usually held monthly. At it, the same junior and senior people review progress in relation to program goals or targets, identify bottlenecks, and agree on the remedial actions to be taken.
- The action report is also monthly. It summarizes the progress made and problems encountered and names those responsible for action. It is sent to all concerned, including officials in higher-level organizations whose functions, such as the release of funds, affect the project work program.

Evaluation of this system in practice indicated that it contributed to improved performance not only because it ensured efficient allocation of project resources but also because it emphasized joint action, reduced any tendency to authoritarian behaviour, and enhanced the morale and motivation of junior staff.

Good operational manuals can be valuable aids to irrigation projects. They should include specification of detailed procedures for building up estimates of water supply and demand and methods for monitoring project performance and the performance of field staff. Unfortunately, many of those that exist are inadequate or old and in need of radical revision: such manuals are useless if not kept up to date.

The provision of training programs is a vitally important matter that is frequently neglected at evident cost to success. There is a particular need for foresters and other senior officials involved in irrigation schemes to receive training (usually in-service) in water management as well as in general program and operations management. In-service training of junior staff should be part of routine project-management programs.

11. Planning

The importance of good planning to project success was emphasized in the introductory chapter where the elements of the planning process were mentioned. Sustained success in irrigation projects depends not only on the supply, timely delivery, and correct application of water but also on the integration of these with the many land-use, forestry, economic, and management and organizational aspects that are relevant in a balanced, comprehensive plan. Successful forest plantation irrigation requires the skillful combination of accumulated knowledge in many professional fields including engineering; water, soil, and plant sciences; silviculture and forest management; economics; and social sciences. Project preparation, appraisal, implementation, and management require experienced judgment based on a high degree of professional competence. Many irrigation projects have been abandoned because of inadequate attention to the need to ensure continued use of all the necessary resources of water, land, and people (Hagan et al. 1968).

Several instances of problems arising from weak planning of irrigated forestry plantations have been mentioned earlier in this review. They include the plea of Wood (1977) for good project planning and avoidance of piecemeal solutions and the constructive criticism by Ahmad (1975) of cases in which problems might have been avoided had the schemes that he reviewed been better conceived, been developed with full cognizance of the results of planning surveys that would have identified waterlogged and saline areas, and entailed the prescription of more realistic annual work targets. Failure was certain in the instance cited by Ahmad and those described by Singh (1963), in which new projects or phases of projects were implemented without correction of errors made in their precursors and in which nobody had the courage to say "it won't work" before the resources were committed. The importance of good planning to the successful management of irrigation projects, as emphasized by Sagardoy et al. (1982), was mentioned in the discussion of organization and management in the previous chapter.

The elements of the planning process are in principle and nature the same whether it is applied to a relatively minor operation or to a large project, to the whole project or any one of its components, whether it is conducted as a discrete forestry project or in conjunction with irrigated agriculture. The discussion that follows is based in large measure on the reviews by Hagan et al. (1968), Gittinger (1982), and pertinent parts of France (1977) and the record of FAO's irrigation planning methodology seminar held in Bucharest in 1971 (FAO 1972).

It is always desirable that there should be a comprehensive policy, entrenched in a legally enforceable system, to provide for orderly development of a country's water resources in order, among other things, to minimize subsequent conflicts between individual users, both within the agriculture and forestry sectors and between them and other users and interests. It is in the interests of all users and agencies concerned

that there be the fullest cooperation from the earliest stages of planning. This might take the form of an integrated river-basin development plan or project, necessitating international agreement when the basin concerns more than one country. Coordination of policy and planning throughout the river basin, at the national or, where appropriate, the regional level, and effective control of irrigation and drainage practices are vital if projects are to flourish in the long term rather than die off as a result, for example, of waterlogging and salinization due to inadequacy of control (Unesco 1974).

The planning or plan formulation process, whether at the national, regional, or project level, comprises five elements:

- Establishment of clear objectives and activities to be undertaken -- usually the responsibility of policymakers and administrators at the appropriate senior level;
- Selection of criteria for the evaluation and comparison of alternatives — these criteria will influence to some extent the type of information to be collected or, conversely, lack of critical information might influence the selection of the criteria to be used;
- Collection of information on the quantity and quality necessary for the success of the planning process;
- Development of alternative plans or components within them for achieving the objectives specified and evaluating and comparing them in economic terms — in general, evaluation, at least when final choices are being made, is done with proper representation of the level from which funds for financing the project are derived; and

In desert areas, cultivated sites — including tree plantations — require protection from inundation and the abrasive action of blowing sand. Near Dongola in the Sudan: Initial development of an irrigated Eucalyptus *shelterbelt — note piled sand cleared from furrows.*

- Selection of the optimum plan — usually the alternative that would lead to the required production at the lowest cost, or the maximum production for a given investment.

The information needed for project planning will comprise that for pertinent aspects of climate, water availability, groundwater, topography, hydrology, soil, salinity, and drainage — that is, concerning the physical environment and water inputs. Information would also be required on factors such as species and varieties that might be grown, seed sources, pests and diseases, silvicultural characteristics and regimes, equipment, machinery, transport, construction materials, personnel, salaries and wages, land-tenure systems, yields, and prices and costs — that is, aspects that have been reviewed and discussed in earlier chapters of this book.

The design of alternative project plans would cover some or all of the phases reviewed in chapters 7, 8, and 10, i.e., those that have to do with selection and detailed design of the water supply; irrigation water requirements; conveyance, distribution, irrigation, and drainage systems; irrigation schedules, including provision for leaching; land clearing, grading, profile improvement, and reclamation; tree crop systems and patterns; production; harvesting; applied research; complementary physical inputs such as fertilizers; storage and timber-handling facilities; marketing; housing; community facilities; extension; appropriate land-tenure arrangements; training; extension organization and management; and costs and prices. In all of these, scale and time dimensions must be built in appropriately.

Economic and financial analysis using one or more of the techniques reviewed in chapter 9 would be used to compare and select from among alternatives of features such as methods of irrigation, machinery and equipment, silvicultural methods and tree crop-management regimes, and for the selection of the best overall plan. Complex analyses of this kind are usually facilitated by computer simulation using models such as that described by Crandall and Luxmore (1982).

The design and planning task is usually complex in the extreme, involving as it does large numbers of aspects, factors, disciplines, and alternatives, virtually at every step. It can seldom be done adequately without inputs from representatives of two or more disciplines.

To contend with some of the complexity, aids in the form of network analysis precedures supported by computers are frequently used in planning. The benefits that may be derived from network analysis of a project are not limited to shortening the time taken to do the planning job. They are considerably more comprehensive than that. The first phase of the planning process, i.e., determining objectives and activities, requires a detailed and rigorous analysis of the project, giving the specialist responsible a comprehensive appreciation of the total system under consideration. Participation of specialists representing each discipline involved leads to useful confrontation and discussion. During this, many unsuspected problems emerge and a number of possible conflicts may be resolved before they occur. Network analysis compels exhaustive thought about project planning itself. Thus, if study of the critical path of the project indicates unacceptable time scales, an adjustment or alternative plan for the project would be sought to achieve a shorter time span. However, network analysis does not itself provide solutions to technical problems or guarantee that a particular method is the optimum one: it is a tool that enables the planner to analyze and visualize the progress of a project as tentatively planned, to identify potential problems of execution or constraints, and to make correcting decisions rapidly. Network analysis is a refined procedure for handling information supplied by two or

more discipline specialists, which accounts for the need to ensure the high quality of that information through rigorous, detailed preliminary analysis of the project. In practice, the work entailed in generating a network can be considerable and the cost therefore high, although probably less so than that of an otherwise poorly designed project.

Planning and management are integral parts of the continuous process usually referred to as the planning cycle, i.e., plan formulation (the planning process described above) through implementation then evaluation to plan reformulation. The second and third elements of this cycle entail budgeting, programing, and monitoring. Good management is not possible without a good plan that is kept current through the application of this cycle.

Appendix 1. Tree Species Used Under Irrigation

Table 7. Growth rates of principal species used.[a]

Species	Country	MAI[b] Volume (m^3/ha)	MAI[b] Age (years)	Remarks	Source
Acacia nilotica[c]	Uttar Pradesh, India	6–8		Canalside average	IBRD reports
Dalbergia sissoo[c]	Pakistan	5.9–10.1	10–20	Quality class 1	Troup (1921)
		4.2–7.6	10–20	Quality class 2	Troup (1921)
		3.1–5.0	10–20	Quality class 3	Troup (1921)
		2.5	—	Average	Lerche and Khan (1967)
		9	—	Potential average	Lerche and Khan (1967)
Eucalyptus camaldulensis[c]	Iraq	16	10	Best sites	Busby (1979)
	Israel	14.3	4	Unirrigated 7.2	Karschon (1970)
		15.8	4	Less water	Karschon (1970)
	Kuwait	25	10	Prediction	Wood and Synott (1978)
	Niger	32	5.5	Total volume	Hamel (1985)
		8–20	3	Range of provenances	Hamel (1985)
		5–13	3	Range of irrigation rates	Hamel (1985)
		16–38	2	Range of spacings	Hamel (1985)
		15–20	—	Prediction for good practice	Gorse[d]
	Nigeria	22	4	Irrigation in 1st year only	Jackson (1976)
	Pakistan	18	—	Prediction for good practice	Pryor[e]
	Zimbabwe[f]	15–27	5.7	Range in 4 sites	Barrett and Woodvine (1971)
		65.5	5.7	Exceptional site	Barrett and Woodvine (1971)
Eucalyptus "hybrid"[g]	Uttar Pradesh, India	12	5	Canalside average	IBRD reports

continued

Table 7. Concluded

Species	Country	MAI[b] Volume (m^3/ha)	MAI[b] Age (years)	Remarks	Source
Eucalyptus microtheca	Sudan[b]	7.3	7.5	Average	Masson and Osman (1963)
		10	—	Average actual	Foggie (1967)
		12	—	Potential average	Foggie (1967)
		23	9	Quality class 1	Ahmed (nd)
		14	9	Quality class 2	Ahmed (nd)
		7	9	Quality class 3	Ahmed (nd)
Eucalyptus resinifera	Niger	42.6	5.5	—	Hamel (1985)
Populus deltoides	Israel	24	4	Clone 'A'	Karschon (1970)
		39	4	Clone 'B'	Karschon (1970)
	Zimbabwe	14	5	—	Barrett and Woodvine (1971)
Black poplar	Iraq	36	5	Best sites	Busby (1979)
Prosopis juliflora[c]	Uttar Pradesh, India	6–8	—	Canalside average	IBRD reports

[a] For discussion of these growth rates, see chapter 8. Growth rates for other species tested in Zimbabwe are shown in the text.
[b] With the exception of *D. sissoo* data from Troup (1921), mean annual increment (MAI) values exclude most branchwood and foliage. An estimate of total biomass production would be given by adding 20–30% of the volumes shown. Troup's data include brushwood below 2.5 cm diameter.
[c] Species that are relatively salt tolerant.
[d] Jean Gorse, World Bank, Washington, DC, USA, personal communication.
[e] In Lerche and Khan (1967).
[f] The rate of increment of natural woodland in the area was 0.6–0.75 m^3/ha per year (Barrett and Woodvine 1971).
[g] *Eucalyptus tereticornis*.
[h] The rate of increment of natural woodland in the area was 0.5–0.6 m^3/ha per year (Foggie 1967).

Appendix 2. Provisional Rating of Salt Tolerance of Trees and Shrubs in Kuwait

Table 8. Ranking according to tolerance of maximum electrical conductivity[a] of soil solution.[b]

EC × 10^3	Species
≧50	*Avicennia marina, Suaeda vermiculata*
40	*Casuarina glauca, Conocarpus lancifolius, Phoenix dactylifera, Tamarix jordanis, T. maris-mortui*
35	*Prosopis stephanianna, P. tamarugo, Tamarix aravensis, T. deserti, T. mannifera, T. orientalis, T. pentandra, T. meveri*
30	*Acacia ligulata, Casuarina equisetifolia, Kochia indica, Prosopis juliflora, Tamarix aphylla, Zizyphus vulgaris*
25	*Tamarix nilotica*
18	*Acacia pendula, A. salicina, Casuarina stricta, Eucalyptus sargentii, E. spathulata, Nerium oleander, Parkinsonia aculeata*
16	*Acacia farnesiana, Callistemon lanceolatus, C. cristata, Eucalyptus camaldulensis* var. *obtusa, E. kondinensis, E. microtheca, Prosopis chilensis, P. juliflora*
14	*Acacia arabica, Casuarina lehmanii, Haloxylon salicornicum, Sesbania grandiflora*
12	*Acacia stenophylla, Cailiris glauca, Dodonea viscosa, Eucalyptus gomphocephala, E. kruseana, Melaleuca pauperifolia, Melia azaderach, Thevetia nerifolia*
10	*Albizzia lebbek, Eucalyptus annulata, E. brachycorys, E. cornuta, E. melliodora, E. stricklandi, Ficus carica, F. religiosa, Lagenaria patersoni, Salvadora oleoides, Thespesia populnea, Vitex agnus-castus*
8.5	*Casuarina cunninghamiana, Dalbergia sissoo, Eucalyptus cladocalyx, E. forestiana, E. grossa, E. lansdowneana, E. largiflorens, E. robusta, E. salubris, Inga dulcis, Terminalia arjuna*
8	*Eucalyptus brockwayi, E. dundasi, E. intertexia, E. woodwardii, Ficus bengalensis, Myrtus communis, Prosopis spicigera, Schinus molle, Terminalia catappa*
6	*Balanites aegyptiaca, Cupressus arizonica, Eucalyptus torquata, Grevillea robusta, Olea europea, Tamarindus indica, Tecoma stans*
5	*Cordia myxa, Cupressus sempervirens* var. *stricta, Elaeagnus angustifolia, Eucalyptus astringens, E. campaspe, E. flocktoniae, E. lansdowneana, E. longicornis, E. patellaris, E. transcontinentalis, Lantana aculeata, Populus euphratica, Terminalia belerica*
4.5	*Bombax malabaricum, Eucalyptus citriodora, Populus folleana*
3	*Acacia tortilis, Ficus sycomorus, Robina pseudacacia, Salix alba*
2.5	*Acacia cyanophylla, A. mellifera, A. raddiana, A. forestiana*
2	*Eucalyptus tereticornis, Hyphaene thebaica, Poinciana regia, Duranta plumieri, Populus oblegata*
1	*Azalea* species, *Bougainvillea* species, *Populus thevestina, P. × euramericana*

[a]Electrical conductivity of soil solution expressed in relative values termed EC × 10^3.
[b]From Firmin (1968).

Table 9. Trees growing successfully near saline wells.[a]

EC × 10^3	Species
59	*Zizyphus* species, *Phoenix* species
51	*Tamarix* species
46	*Prosopis juliflora*
22.5	*Tamarix aphylla, Eucalyptus camaldulensis, Nerium oleander, Parkinsonia aculeata, Inga dulcis, Acacia farnesiana, A. nilotica*

[a]From Firmin (1968).

Table 10. Trees growing over water tables of various ionic ratios.[a]

Na/Ca	Species	Na/Ca + Mg	Species
16.4	*Prosopis* species	4.7	*Zizyphus* species
12.75	*Zizyphus* species	3.8	*Prosopis* species
11.4	*Phoenix* species	3.3	*Eucalyptus camaldulensis, Nerium oleander, Tamarix aphylla, A. farnesiana*
8.8	*Eucalyptus camaldulensis*		
6.5	*Parkinsonia aculeata, Acacia farnesiana*		

[a]From Firmin (1968).

Appendix 3. Successful Tree Species Under Saline Irrigation at Eilat, Israel[1]

Superior Performance

Acacia cyanophylla, A. longifolia, A. raddiana, A. spirocarpa, Albizia species, *Balanites aegyptica, Capparis aegyptica, Cordia myxa, Dalbergia sissoo, Eucalyptus camaldulensis, E. gomphocephala, Ficus nitida, F. sycamorus, Haloxylon salicornicum, Hyphaenae thebaica, Nerium oleander, Parkinsonia aculeata, Phoenix dactilifera, Poinciana regia, Schinus terebrinthifolius, Tamarix articulata, Thevetia nereifolia, Vitex agnus, V. pseudonegundo, Washingtonia filifera, Zizyphus spina-christi*

Good Performance

Acacia cawen, A. farnesiana, A. karroo, A. melanoxylon, Cassia obovata, C. sturtii, Casuarina cunninghamii, Ceratonia siliqua, Dracaena draco, Elaeagnus angustifolia, Ficus carica, Haloxylon persicum, Melaleuca myrtifolia, Morus alba, Olea europea, Schinus molle

Appendix 4. Species Tolerant of Interrupted Irrigation at Khartoum, Sudan[2,3]

Highly resistant

Acacia farnesiana, A. mellifera,[4] *A. nilotica,*[4] *A. senegal, Conocarpus lancifolius*

Moderately resistant

Albizia lebbek, A. procera, Cassia auriculata, C. siamea,[4] *Casuarina equisetifolia, Dalbergia sissoo, Dicrostachys cinerea, Eucalyptus microtheca, E. tereticornis* ("hybrid")

Some resistance

Ceiba pentandra, Combretum aculeatum, Dendocalamus strictus,[4] *Eucalyptus camaldulensis, E. gomphocephala, E. microcorys, E. tereticornis, Khaya senegalensis,*[4] *Leucaena glauca,*[4] *Pongamia pinnata, Populus* × *euramericana, Stereospermum kunthianum*[4]

[1]From Boyko and Boyko (1968).
[2]From Bosshard (1966c).
[3]The number of species tested was limited to those in use in the area.
[4]Limited evidence.

Bibliography

Key Sources

Chapter 2. The Arid Zone Environment
Climate — Fuchs (1973a), Jones et al. (1981), Kaul (1970), Reitan and Green (1968), Thornthwaite and Hare (1955)
Geomorphology — Jones et al. (1981), Lustig (1968)
Soils — Dan (1973), Kaul (1970)
Hydrology and water resources — Buras (1973a), Jones et al. (1981), Mandel (1973)
Drainage and salinity — Elgabaly (1971), Mandel (1973), Shah Mohammad (1978)
Vegetation — Gindel (1973), McGinnies (1968)

Chapter 3. Irrigated Forest Plantation Experience
General background — Eckholm (1975), Unesco (1974)
Regional and country accounts
South Asia and the Middle East
Pakistan — Ali (1960, 1962), Lerche and Khan (1967), Shah Mohammad (1978), Sheikh (1980 and others)
India — Reports of the World Bank, several local papers including Gupta (1979)
Iraq — Busby (1979), Gorrie (1956), Pryor (1953)
Kuwait — Firmin (1968, 1971), Wood and Synott (1978)
United Arab Emirates — Barbier (1978), Satchell (1978), Wood et al. (1975)
Other Middle Eastern countries — Khatib (1971)
The Mediterranean region
Tunisia — Aşar (1975), Cointepas (1968), Van Hoorn et al. (1968)
Algeria — Durand (1958), Metro (in Kaul 1970)
Egypt — Khatib (1971)
Israel — Boyko and Boyko (1968), Karschon (1970), Rawitz et al. (1966)
East, West, and Southern Africa
Sudan — Ahmed (1977, nd), Ali (1979), Bosshard (1966a–e), Foggie (1967), Khan (1966a–d), Masson and Osman (1963)
Mali — IDRC (1981)
Niger — Barbier (1977), Barbier and Louppe (1980), Hamel (1985), Jean Gorse (World Bank, Washington, DC, USA, personal communication)
Nigeria — Allan (1977), Pryor (1970)
Sénégal — Hamel (1985)
Zimbabwe — Barrett and Woodvine (1971)
North America
United States of America — Alverson (1975), De Bell (1975), Woodman (1971, 1973)
South and Central America — FAO (1979)
Australia — Edgar and Stewart (1979), Nichols and Waring (1977)

Chapter 4. Some Basic Concepts
Plant–soil–atmospheric water relationships
Water relationships — Fuchs (1973a, c), Gairon (1973), Gairon and Hadas (1973), Hadas (1973a, b), Plaut and Moreshet (1973), Thornthwaite and Hare (1955)
Irrigation and soil properties — Bresler (1973), Doneen (1972), Kalkafi (1973), Meiri and Levy (1973), Yaron and Shainberg (1973)
Irrigation and topography — Doneen (1972), Lustig (1968)
Hydrological implications of irrigation — Jones et al. (1981), Lustig (1968)

Chapter 5. Irrigation Systems
General — Booher (1974), Vermeiren and Jobling (1980)
Gravity systems — Ali (1960), Booher (1974), France (nd), Rawitz (1973b)
Sprinkler systems — Pillsbury (1968), Rawitz (1973a)
Localized systems — France (1977), Heller and Bresler (1973), SETI (nd), Vermeiren and Jobling (1980), Wood et al. (1975)

Chapter 6. Assessment of Needs and Potentialities
Population and socioeconomic trends — Foggie (1967), Glesinger (1960)
Need for tree products — Barbier and Louppe (1980), Delwaulle (1979), Foggie (1967)
Technical feasibility
Water for irrigation — Bielorai (1973), Doorenbos and Pruitt (1977), Shalhevet (1973), Yaron (1973)
Tree species for irrigation — See appendices 1–4. Also Goor and Barney (1968), Pryor (1953, 1970, and others)
Tolerance of waterlogging and salinity — Meiri and Levy (1973), Meiri and Shalhevet (1973)
Root systems — Bielorai (1973), Bielorai et al. (1973), Bosshard and Wunder (1966)
Tree growth and wood quality — Barrett and Woodvine (1971), Nichols and Waring (1977)
Socioeconomic feasibility — Ali (1979), Banks (in Barrett and Woodvine 1971), Foggie (1967), Gupta (1979), Hamel (1985), Khan (1966), Lerche and Khan (1967)

Chapter 7. Development of Irrigated Plantations
Land use and tenure — Glesinger (1960), Swaminathan (1980)
Physical and ecological survey — Yaron and Vink (1973)
Assessment and development of water resources — Buras (1973a, b)
Design of irrigated production systems
Irrigation systems and water regimes — Booher (1974), Doneen (1972), France (1969, nd), Khatib (1971), NAS (1974), Rawitz (1973a, b), Shalhevet (1973)

Chapter 8. Implementation and Production
General — See text

Chapter 9. Economics of Irrigated Plantations
Economic analysis and evaluation — France (1977), Gittinger (1982), Openshaw (1980), Pillsbury (1968), Sagardoy et al. (1982)

Chapter 10. Organization and Management
General — France (nd), Sagardoy et al. (1982)

Chapter 11. Planning
General — FAO (1972), France (1977), Gittinger (1982), Hagan et al. (1968)

References

Ahmad, J. 1975. Management of irrigated plantations in Kotri Barrage zone. Pakistan Journal of Forestry, 25(1), 26–30.

Ahmed, A. El Houri. nd [1969]. Introduction to the silviculture of *Eucalyptus microtheca* in the Gezira. University of Khartoum, Khartoum, Sudan. M.Sc. thesis, 19 pp.

——— 1977. The silviculture and management of *Eucalyptus microtheca* in irrigated plantations in the Gezira of the Sudan. Forest Research Institute, Sudan Forest Administration, Khartoum, Sudan. Bulletin 3, 18 pp.

Ali, G.E.F. 1979. The appraisal of irrigated plantations in the Gezira in Northern Sudan. University College of North Wales, Bangor, U.K. M.S. thesis, 130 pp.

Ali, Z. 1960. Principles and practice of irrigation in the irrigated plantations of West Pakistan. West Pakistan Forest Department, Peshawar, Pakistan. Record 3, 249 pp.

——— 1962. Forestry practices in the irrigated forest plantations of West Pakistan. West Pakistan Forest Department, Peshawar, Pakistan. Record 7, 97 pp.

Allan, T.G. 1977. Handbook of plantation establishment techniques in the Nigerian savanna. FAO, Rome, Italy. Savanna Forestry Research Station Project Document DP, NIR/73/007, 64 pp.

Alverson, J.E. 1975. Wastewater irrigation and forests [in Pacific Northwest]. In Water spectrum: Issues, choices, actions. U.S. Army, Corps of Engineers, Washington, DC, USA. 6(4), 29–36.

Arar, A. 1975. Quality of water in relation to irrigating sandy soils. In Sandy soils: Report on the FAO–UNDP Seminar on reclamation and management of sandy soils in the Near East and North Africa, Nicosia, 3–8 December 1973. FAO, Rome, Italy. Soils Bulletin 25, 73–83.

Armitage, F.B., Joustra, P.A., Ben Salem, B. 1980. Genetic resources of tree species in arid and semi-arid areas. FAO, Rome, Italy. 118 pp.

Ashraf Ali, M. 1971. Climate and hydrology in West Pakistan: A summary. Soils Research Institute, Lahore, Pakistan. Soils Bulletin, 23 pp.

Ayers, R.S., Westcot, D.W. 1976. Water quality for agriculture. FAO, Rome, Italy. Irrigation and Drainage Paper 29, 97 pp.

Badi, K.H. 1967. Afforestation in the clay plains of Kassala Province. Sudan Forest Department, Khartoum, Sudan. Bulletin 13, 20 pp.

Barbier, C. 1977. Rapport de stage: Plantation expérimentale d'*Eucalyptus* en irrigué. Ministre de l'éducation nationale, Direction de l'enseignement supérieur et de la recherche scientifique, Bamako, Mali. 33 pp.

_____. 1978. L'irrigation des arbres forestiers. Rapport à Seminaire forestier, CILSS/DSE, Ouagadougou, Sénégal, janvier 1978. Comité permanent inter-états de lutte contre la sécheresse dans le Sahel, Ouagadougou, Sénégal. 11 pp.

Barbier, C., Louppe, D. 1980. Interventions forestières sur l'unité expérimentale de cultures irriguées de Lossa (Niger): Première campagne, 1978–1979. Centre technique forestier tropical, Nogent-sur-Marne, France. 32 pp.

Barbier, C., Quideau, P., Boguetteau, K. 1981. Bilan des interventions forestières sur l'unité expérimentale des cultures irriguées de Lossa (Niger). Institut national de recherches agronomiques du Niger and Centre technique forestier tropical, Nogent-sur-Marne, France. 28 pp.

Barghava, O.P. 1948. Saline and alkaline soils and their afforestation problem. Indian Forestry, 74(8), 303–306. (Cited in Sheikh 1974b.)

Barlow, B.A. 1983. Casuarinas — a taxonomic and biographic review. In Proceedings of the casuarina ecology, management and utilization international workshop, Canberra, Australia. Commonwealth Scientific and Industrial Research Organization, Canberra, Australia. 10–18.

Barrett, R.L., Mullin, L.J. 1968. A review of introductions of forest trees in Rhodesia. Government Printer, Harare, Rhodesia. Rhodesia Bulletin of Forest Research, 1, 227 pp.

Barrett, R.L., Woodvine, F. 1971. Possibilities for irrigated forestry in the Rhodesian low veld. Rhodesia Forestry Commission, Harare, Rhodesia. Research Paper 1, 50 pp.

Bayoumi, A.A. 1972. The role of shelterbelts in the Sudan Gezira. Oxford University, Oxford, U.K. M.Sc. dissertation, 55 pp.

_____. 1976. The role of shelterbelts in Sudanese irrigated agriculture with particular reference to the Gezira. Sudan Sylva, 21, 24–39.

_____. 1977. The role of shelterbelts in Sudanese irrigated agriculture with special reference to the Gezira. Sudan Sylva, 22, 25–39.

Belanger, R.P., Saucier, J.R. 1975. Intensive culture of hardwoods in the South. Iowa Journal of Research, 49(3), part 2, 339–344.

Belshaw, D., Chambers, R. 1973. A practical management system for implementing rural development programmes and projects. Institute for Developmental Studies, University of Nairobi, Nairobi, Kenya. Discussion Paper 162, 35 pp. (Later published in Sagardoy et al. 1982.)

Bhatia, K.S. 1980. The growth of *Eucalyptus* hybrid (*E. tereticornis*) on eroded alluvial soils of Uttar Pradesh in relation to spacing, irrigation and manuring. Indian Forester, 106(10), 738–743.

Bielorai, H. 1973. Prediction of irrigation needs [of water]. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 359–368.

Bielorai, H., Levin, I., Assaf, R. 1973. Irrigation of fruit trees. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 203–213.

Bohorquez Rejas, A. 1972. El *Eucalyptus globulus*: Regeneración natural, producción y costos en el valle del Rio Mantaro (Perú). In Proceedings of the 7th World Forestry Congress. 1783–1788.

Booher, L.T. 1974. Surface irrigation. FAO, Rome, Italy. Agricultural Development Paper 95, 160 pp.

Bosshard, W.C. 1966a. Irrigation methods in the Khartoum Greenbelt. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 1, 22 pp.

_____. 1966b. Irrigation methods in the Khartoum Greenbelt. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 21, 25 pp.

_____. 1966c. Tree species for the Khartoum Greenbelt and other irrigated plantations in arid zones. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 22, 49 pp.

_____. 1966d. Sowing and planting under arid conditions. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 31, 62 pp.

_____. 1966e. Drought resistance of tree species. Sudan Forest Department, Khartoum, Sudan, and United

Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 32, 45 pp.

Bosshard, W.C., Wunder, W.G. 1966. Root studies in irrigated tree plantations. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 29, 50 pp.

Boyko, E., Boyko, H. 1968. The desert garden of Eilat. In Boyko, H., ed., Saline irrigation for agriculture and forestry. Junk N.V., The Hague, The Netherlands. 133–160.

Brennan, P.J. 1983. Manual on taxonomy of *Acacia* species. FAO, Rome, Italy. 47 pp.

Bresler, E. 1973. Solute movement in soils. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 165–175.

Briskin, R.L., Murphey, W.K. 1970. Influence of sewage effluent irrigation on physical and mechanical properties of plantation-grown red pine. School of Forest Resources, Pennsylvania State University, University Park, PA, USA. Research Briefs, 1, 1–3.

Buras, N. 1973a. Hydrological fundamentals. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 31–40.

——— 1973b. Development and management of water resources. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 51–69.

Burley, J., Wood, P.J. 1976. A manual on species and provenance research with particular reference to the tropics. Commonwealth Forestry Institute, Oxford, U.K. Tropical Forestry Papers 10 and 10A, 233 and 64 pp.

Busby, R.J.N. 1979. An economic evaluation of the prospects for irrigated industrial plantations on the Mesopotamian Plain (final report). FAO, Baghdad, Iraq. FO: DP/IRQ/76/002, Field Document 3, 39 pp.

Carretero, R.V. 1972. Contribución al estudio del comportamiento y productividad de un cultivo de alamo bajo riego en el valle de Tunuyan, Provincia de Mendoza, Argentina. In Proceedings of the 7th World Forestry Congress. 1596–1604.

Chardenon, J. 1969. La culture du peuplier en Turquie et son amelioration. In Institut du Peuplier Turquie, Rapport technique volume II. FAO, Rome, Italy. FAO/SF, 41/TUR6, 165–217.

Chaturvedi, A.N., Sharma, S.C., Srivastava, R. 1984. Water consumption and biomass production of some forest trees. Commonwealth Forestry Review, 63(3), 217–223.

Clements, H.F. 1934. Significance of transpiration. Plant Physiology, 9, 165–172.

Cointepas, J.P. 1968. Irrigation with salt water and drainage in Tunisia. In Boyko, H., ed., Saline irrigation for agriculture and forestry. Junk N.V., The Hague, The Netherlands. 187–194.

Costin, A.B., Dooge, C.I. 1973. Balancing the effects of man's actions on the hydrological cycle. In Man's influence on the hydrological cycle. FAO, Rome, Italy. Irrigation and Drainage Paper 17, 19–51.

Crandall, D.A., Luxmore, R.J. 1982. Simulated water budgets for an irrigated sycamore phytomass farm. Forest Science, 28(1), 17–30.

Dan, J. 1973. Arid zone soils. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 11–28.

De Bell, D.S. 1975. Short-rotation culture of hardwoods in the Pacific North-West. Iowa State Journal of Research, 49(3), part 2, 345–352.

De Bell, D.S., Brunette, A., Schweitzer, D.L. 1977. Expectations from intensive culture on industrial forest lands. Journal of Forestry, 75(1), 10–13.

Delwaulle, J.-C. 1979. Plantations forestières en Afrique tropicale sèche: Troisième partie — Techniques à utiliser de la plantation à l'exploitation et aux rejets. Revue des Bois et Forêts des Tropiques, 186 (juillet–août), 32 pp.

Dickmann, D.I. 1975. Plant materials appropriate for intensive culture of wood-fibre in the North Central Region. Iowa State Journal of Research, 49(3), part 2, 281–286.

Doneen, I.D. 1972. Irrigation practice and water management. FAO, Rome, Italy. Irrigation and Drainage Paper 1, 84 pp.

Doorenbos, J., Pruitt, W.O. 1977. Guidelines for predicting crop water requirements. FAO, Rome, Italy. Drainage and Irrigation Paper 24, 143 pp.

Durand, J.H. 1958. Les périmètres irrigables expérimentales de Sahara Occidental. Terres et Eaux, 31, 10–33.

Eccher, A., Lubrano, L. 1969. Prova di irrigazione estiva al *P. radiata* D. Don. Cellulosa e Carta, 20(4), 17–27.

Eckholm, E.P.C. 1975. Losing ground: Environmental stress and world food prospects. Chapter 7: The salting and silting of irrigation systems. W.W. Norton, New York, NY, USA. 114–135 and 213–214.

Edgar, J.G., Stewart, H.T.L. 1979. Wastewater disposal and reclamation using *Eucalyptus* and other trees. Pergamon Press, Oxford, U.K. Progress in Water Technology, 11(4/5), 163–173.

Elgabaly, M.M. 1971. Reclamation and management of salt affected soils. In Salinity seminar, Baghdad. FAO, Rome, Italy. Irrigation and Drainage Paper 7, 50–79.

Evenari, M., Nessler, U., Rogel, A., Schenk, O. 1975. Antike Technik in Dienste der Landwirtschaft in ariden Gebieten. Der Tropenlandwirt. Zeitschrift fur die landwirtschaft in den Tropen und Subtropen, 76(Jahrgang), 11–21.

FAO (Food and Agriculture Organization). 1969. Final report: Forestry Research and Education Centre, the Sudan. FAO, Rome, Italy. FAO/SF, 70/SUD 3, 170 pp.

_____. 1972. Planning methodology seminar, Bucharest. FAO, Rome, Italy. Irrigation and Drainage Paper 11, 128 pp.

_____. 1979a. Eucalypts for planting. FAO, Rome, Italy. FAO Forestry Series, 11, 677 pp.

_____. 1979b. Poplars and willows in wood production and land use. FAO, Rome, Italy. FAO Forestry Series, 10, 328 pp.

Felker, P., Cannell, G.H., Osborn, J. 1983. Effects of irrigation on biomass production of 32 *Prosopis* (mesquite) accessions. Experimental Agriculture, 19(2), 187–198.

Ferlin, G.R. 1977. Rôle du forestier Sahélien. Bois et Forêts Tropicals, 171, 5–14.

Ficco, N. 1968. Irrigation with saline water in Puglia. In Boyko, H., ed., Saline irrigation for agriculture and forestry. Junk N.V., The Hague, The Netherlands. 162–167.

Firmin, R. 1968. Forestry trials with highly saline or sea-water in Kuwait. In Boyko, H., ed., Saline irrigation for agriculture and forestry. Junk N.V., The Hague, The Netherlands. 107–132.

_____. 1971. Afforestation: Report to the Government of Kuwait. FAO, Rome, Italy. Report FAO/KU/TF 46, 29 pp.

Foggie, A. 1967. Report to the Government of the Sudan on forestry and forest policy in the Gezira area. FAO, Rome, Italy. Report TA 2411, 95 pp.

Fowler, W.B., Helvey, J.D. 1974. Effect of large scale irrigation on climate in the Columbia Basin. Science, 184(4133), 121–127.

France. 1969. Les ouvrages d'un petit réseau d'irrigation. In Collection techniques rurales en Afrique. Secrétariat d'État aux Affaires Étrangères, Paris, France. 185 pp.

_____. 1977. Manuel de gestion des périmètres irrigués. In Collection techniques rurales en Afrique. Ministre de la Coopération, Paris, France. 24 pp.

_____. nd [1977]. Irrigation gravitaire par canaux: Conception du périmètre, étude des canaux et leurs revêtements. In Collection techniques rurales en Afrique. Ministre de la Coopération, Paris, France. 296 pp.

Fuchs, M. 1973a. Climate and irrigation. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 3–9.

_____. 1973b. Water transfer from the soil and the vegetation to the atmosphere. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 143–152.

_____. 1973c. The estimation of evapotranspiration. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 241–247.

Gairon, S. 1973. Important soil characteristics relevant to irrigation. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 227–240.

Gairon, S., Hadas, A. 1973. Measurement of water status in soils. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 215–226.

Gindel, I. 1964. Seasonal fluctuations in soil moisture under the canopy of xerophytes and in open areas. Commonwealth Forestry Review, 43, 219–234.

_____. 1971. Transpiration of three *Eucalyptus* species as a function of solar energy, soil moisture and leaf area. Physiologia Plantarum, 24, 143–149.

_____. 1973. A new ecophysiological approach to forest-water relationships in arid climates. Junk N.V., The Hague, The Netherlands. 142 pp.

Gittinger, J.P. 1982. Economic analysis of agricultural projects. Johns Hopkins University Press, Baltimore, MD, USA. 505 pp.

Giunchi, A.J. 1972. Los alamos y la salinidad de los suelos. In Proceedings of the 7th World Forestry Congress. 1811–1815.

Glesinger, E. 1960. The Mediterranean project. Scientific American, 203(1), 86–105.

Goor, A.Y., Barney, C.W. 1968. Forest tree planting in arid zones. Ronald Press, New York, NY, USA. 460 pp.

Gorrie, R.M. 1956. Prospects for irrigated forest plantations in Iraq. Commonwealth Forestry Review, 35(1), 72–76.

Grossi, P. 1974. [Consideration and research on forest irrigation.] Monti e Boschi V, 25(4), 23–31.

_____. 1976. [Consideration and research on forest irrigation: Contribution II.] Monti e Boschi V, 27(3), 9–15.

Gupta, T. 1979. Some financial and natural resource management aspects of commercial cultivation of irrigated *Eucalyptus* in Gujarat, India. Indian Journal of Forestry, 2(2), 118–137.

Hadas, A. 1973a. Water retention and flow in soils. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 89–109.

——— 1973b. Water transfer from soil to plant. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 111–122.
Hagan, R.M., Houston, C.E., Allison, S.V. 1968. Successful irrigation. FAO, Rome, Italy. Land and Water Development Series 5, 53 pp.
Hakim, K.A. 1951. Critique of irrigated plantations in the Punjab. Pakistan Journal of Forestry, 2, 264–270.
Hall, N. et al. 1972. The use of trees and shrubs in the dry country of Australia. Forestry and Timber Bureau, Canberra, Australia. 588 pp.
Hallsworth, E.G. 1981. The use of saline groundwater in arid areas. Experimental Agriculture, 17, 145–147.
Hamel, O. 1985. Production ligneuse en irrigue dans les perimetres amenages du Sahel Nigerien et Sénégalais. Centre technique forestier tropical, Nogent-sur-Marne, France, and Institut Sénégalais de la recherche agricole, Dakar, Sénégal. 55 pp.
Hassan, M.N., Marei, S., Motagalli, M., El Abd, H., Arnaout, Z. 1979. Salinity hazard and water logging in the area west of Noubaria Canal. In Advances in desert and arid land technology and development. Harwood-Academic Publishers, Chur, Switzerland. 85–95.
Heller, J., Bresler, E. 1973. Trickle irrigation. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 339–351.
Hiley, W.E. 1930. The economics of forestry. Clarendon Press, Oxford, U.K. 256 pp.
Holmes, J.W., Colville, J.S. 1970. Grassland hydrology in a karstic region of Southern Australia: II — Forest hydrology in a karstic region of Southern Australia, 10, 38–74. (Cited in Edgar and Stewart 1979.)
Hughes, J.D., Thirgood, J.V. 1982. Deforestation in ancient Greece and Rome: A cause of collapse. The Ecologist, 12(5), 196–207.
IBRD (International Bank for Reconstruction and Development). 1978. Proposed credit to the Republic of Niger for a forestry project. World Bank, Washington, DC, USA. Report P-2218 NIR, 17 pp.
——— 1979a. Mali forestry project. World Bank, Washington, DC, USA. Staff Appraisal Report 2148a-MLI, 25 pp.
——— 1979b. Uttar Pradesh social forestry project, India. World Bank, Washington, DC, USA. Staff Appraisal Report 2386a-IN, 39 pp.
——— 1982. Niger pilot and technical assistance forestry project: Completion report. World Bank, Washington, DC, USA. IBRD Credit 800-NIR, 29 pp.
IDRC (International Development Research Centre). 1981. Irrigated plantations in Mali: Proposals for phase II. IDRC, Ottawa, Canada. Project summary 3-P-80-0184, 14 pp.
Jackson, J.K. 1976. Irrigated plantations. In Savannah afforestation in Africa. FAO, Rome, Italy. TF-RAF-95(DEN), 168–172.
James, A.R. 1973. Drought conditions in the pressure water zone of north-eastern Nigeria — Some provisional observations. Savanna, 2(2), 108–114.
Johnson, L.A.S. 1980. Notes on Casuarinaceae. Telopea, 2(1), 83–84.
——— 1982. Notes on Casuarinaceae II. Journal of the Adelaide Botanical Gardens, 6(1), 73–87.
Johnson, R.D., Hall, N. 1970. [Afforestation in arid zones of] Australia. In Kaul, R.N., ed., Afforestation in arid zones. Junk N.V., The Hague, The Netherlands. 385–414.
Jones, K.R., Berney, O., Carr, D.P., Barrett, E.C. 1981. Arid zone hydrology for agricultural development. FAO, Rome, Italy. Irrigation and Drainage Paper 37, 271 pp.
Kadambi, K. 1946. The Induval irrigated *Casuarina* plantations. Proceedings of the 7th Indian Silvicultural Conference. 580–585.
——— 1951. Study of *Trichosporium* disease in the Induval irrigated *Casuarina* plantations, Mysore State. In Proceedings of the 8th Indian Silvicultural Conference. Part 2, 332–333.
Kalkafi, H. 1973. Nutrient supply of irrigated crops. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 177–188.
Kanshik, R.C. 1961. Problems of irrigated forest plantations. In Proceedings of the 10th Silvicultural Conference, Dehra Dun. Volume 1, 469–477.
Karschon, R. 1970. The effect of irrigation upon the growth of *Eucalyptus camaldulensis* Dehn: Report to 4th Session, Committee on Mediterranean Forest Research, Ankara. FAO, Rome, Italy. 4 pp.
Kaul, R.N. 1970. Afforestation in arid zones. Junk N.V., The Hague, The Netherlands. 435 pp.
Khan, A.H., Asgar, A.G., Rasul, G. 1956. Observations on the mortality of shisham (*Dalbergia sissoo*) and other trees in the Khanewal Plantation. Pakistan Journal of Forestry, 6(2,3,4), 109–126, 203–220, 289–301.
Khan, A.H., Bokhari, A.S. 1970. Damage due to fungus diseases in Bhagat Reservoir Plantation, Lyallpur Forest Division. Pakistan Journal of Forestry, 20(3), 293–312.
Khan, A.S. 1966. An appraisal of the existing water utilization practices in irrigated plantations. In Proceedings of the 2nd Pakistan Silvicultural Conference, Peshawar. 149–158.
Khan, M.A.W. 1966a. Results of differential irrigation in a plantation of *Eucalyptus microtheca* during the first year. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 3, 28 pp.

——— 1966b. Effective ridging patterns and standards for seasonally flooded mud flats on the White Nile. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 24, 16 pp.
——— 1966c. Vegetative propagation by culm cuttings in *Bambusa vulgaris* and *Oxytenanthera abyssinica*. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 37, 14 pp.
——— 1966d. Growth of *Eucalyptus microtheca* in conjunction with agricultural and fodder crops. Sudan Forest Department, Khartoum, Sudan, and United Nations Development Programme, New York, NY, USA. Forest Research and Education Project Pamphlet 35, 9 pp.
Khan, M.I.R. 1960a. Shisham (*Dalbergia* Rob.) natural root sucker regeneration versus artificial stump planting in the Changa Manga Irrigated Forest Plantation. Pakistan Journal of Forestry, 10, 31–38.
——— 1960b. Forestry in the Thal. Pakistan Journal of Forestry, 10, 200–208.
——— 1961. Irrigated forest plantations of West Pakistan. Pakistan Journal of Forestry, 11, 154–161.
Khan, S.M., Sheikh, M.I. 1983. To develop techniques for utilizing arid and semi-arid lands through planting under dry conditions. In Annual Research Report for 1982. Pakistan Forestry Institute, Peshawar, Pakistan. 84 pp.
Khatib, A.B. 1971. Present and potential salt affected and waterlogged areas in the countries of the Near East in relation to agriculture. In Salinity seminar, Baghdad. FAO, Rome, Italy. Irrigation and Drainage Paper 7, 13–38.
Khattack, G.M. 1976. History of forest management in Pakistan — III: Irrigated plantation and riverain forest. Pakistan Journal of Forestry, 26(4), 231–241.
Kramer, P.J. 1949. Plant and soil water relationships. McGraw-Hill, New York, NY, USA. 347 pp.
Laurie, M.V. 1974. Tree planting practices in African savannas. FAO, Rome, Italy. Forestry Development Paper 19, 185 pp.
Lerche, C., Khan, A.S. 1967. Economic management of irrigated plantations in West Pakistan. Pakistan Forest Institute, Peshawar, Pakistan. 38 pp.
Louppe, D. 1979. Les plantations irriguées de Karma: Cinq années d'observations. Institut national de recherches agronomiques du Niger, Niamey, Niger. 21 pp.
Lustig, L.K. 1968. Geomorphology and surface hydrology of desert environments. In McGinnies, W.G., Goldman, B.J., Paylore, P., ed., Deserts of the World. University of Arizona Press, Tucson, AZ, USA. 91–285.
Mace, A.C., Gregersen, H.M. 1975. Evaluation of irrigation as an intensive cultural practice for forest crops. Iowa State Journal of Research, 49(3), part 2, 305–312.
Mandel, S. 1973. Hydrology of arid zones. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 39–49.
Masson, J.L., Osman, S. 1963. The Gezira irrigated plantations. FAO, Rome, Italy. FAO/SACAFTECH-Field 3, 11 pp.
Mather, T.H., Trin Ton That. 1984. Environmental management for vector control in rice fields. FAO, Rome, Italy. Irrigation and Drainage Paper 41, 152 pp.
Mathur, C.M. 1961. Irrigated plantations in Rajasthan. In Proceedings of the 10th Silvicultural Conference, Dehra Dun. Volume 1, 477–480.
McGinnies, W.G. 1968. Appraisal of research on vegetation of desert environments. In McGinnies, W.G., Goldman, B.J., Paylore, P., ed., Deserts of the World. University of Arizona Press, Tucson, AZ, USA. 381–474.
McGinnies, W.G., Goldman, B.J., Paylore, P., ed. 1968. Deserts of the World. University of Arizona Press, Tucson, AZ, USA. 788 pp.
Mehdizadeh, P., Kowsar, A., Vaziri, E., Boersma, L. 1978. Water harvesting for afforestation: I — Efficiency and life span of asphalt cover. Journal of Soil Science Society of America, 42(4), 644–649.
Meiggs, R. 1982. Trees and timber in the ancient Mediterranean world. Clarendon Press, Oxford, U.K. 403 pp.
Meigs, P. 1953. World distribution of arid and semi-arid homoclimates. In Reviews of research on arid zone hydrology. Unesco, Paris, France. Arid Zone Programme 1, 203–210.
Meiri, A., Levy, R. 1973. Evaluation of salinity in soils and plants. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 289–299.
Meiri, A., Shalhevet, J. 1973. Crop growth under saline conditions. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 277–290.
Mendizabal, M., Verdejo, G. 1968. A new way of culture to decrease salinity. In Boyko, H., ed., Saline irrigation for agriculture and forestry. Junk N.V., The Hague, The Netherlands. 195–197.
NAS (National Academy of Science). 1974. More water for arid lands: Promising technologies and research opportunities. NAS, Washington, DC, USA. 137 pp.
Nichols, J.W.P. 1971. The effect of environmental factors on wood characteristics. I — The influence of irrigation on *Pinus radiata* from South Australia. Silvae Genetica, 20, 26–33.

Nichols, J.W.P., Waring, H.D. 1977. The effect of environmental factors on wood characteristics. Silvae Genetica, 26(2–3), 107–111.
Nigeria. 1957. Forest research in Nigeria, 1954/55. Lagos, Nigeria. p. 12.
Nishat, H.A. 1978. Reclamation of salt-affected soils. In Proceedings of the Workshop/Seminar on membrane biophysics and salt tolerance in plants. University of Agriculture, Faisalabad, Pakistan. 104–110.
Openshaw, K. 1980. Cost and financial accounting in forestry. Pergamon Press, Oxford, U.K. 188 pp.
Ovrut, B.A., Ovrut, S. 1977. Sahara: The growing giant. Science Digest, 1977(February), 28–32.
Palmberg, C. 1981. A vital genepool is in danger. Unasylva, 33, 22–30.
Pillsbury, A.F. 1968. Sprinkler irrigation. FAO, Rome, Italy. Agricultural Development Paper 88, 179 pp.
——— 1981. The salinity of rivers. Scientific American, 1981(July), 55–65.
Plaut, Z., Moreshet, S. 1973. Transport of water in plant–atmosphere system. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 123–141.
Prevosto, M. 1971. [First results of the effects of irrigation on production and revenue from one rotation of poplar in the Po Valley.] Paper to 14th Session, International Poplar Commission, Romania. FO: CIP/71/59, 13 pp.
Pryor, L.D. 1953. *Eucalyptus* in Iraq — Present and future. FAO, Rome, Italy. Report 169, TA 204/5/6, Project IRQ/10, 28 pp.
——— 1970. Present performance and prospects for future development of plantations of *Eucalyptus*. FAO, Rome, Italy. UNDP Project FOR: SF/NIR 16, Technical Report 2, 10 pp.
Quraishi, M.A.A., Khan, G.S. 1979. Farm forestry in Pakistan. Agricultural University, Faisalabad, Pakistan. Bulletin of Department of Forestry, Range Management and Wildlife, 153 pp.
Raeder-Riotzsch, J.E. 1965. Report to the Government of Iraq on forestry research. FAO, Rome, Italy. Report 2031, 12 pp.
Raeder-Riotzsch, J.E., Masrur, A. 1968. Water consumption of tree seedlings. Pakistan Forest Institute, Peshawar, Pakistan. 7 pp.
Rawitz, E. 1973a. Sprinkler irrigation. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 304–322.
——— 1973b. Gravity irrigation. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 323–337.
——— 1973c. Special irrigation methods and accessory devices. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 353–355.
Rawitz, E., Karschon, R., Mitrani, K. 1966. Growth and consumptive use of two poplar clones under different irrigation regimes. In Irrigation of field and orchard crops under semi-arid conditions. Israel Journal of Agricultural Research, 16, 77–78.
Reitan, C.H., Green, C.R. 1968. Appraisal of research on weather and climate of desert environments. In McGinnies, W.G., Goldman, B.J., Paylore, P., ed., Deserts of the World. University of Arizona Press, Tucson, AZ, USA. 21–92.
Sagardoy, J.A., Bottrall, A., Uitenbogaard, G.O. 1982. Organization, operation and maintenance of irrigation schemes. FAO, Rome, Italy. Irrigation and Drainage Paper 16, 166 pp.
Saleem, A.A. 1973. A study of shelterbelt experiences in semi-arid areas with particular reference to application in the Sudan. University of Edinburgh, Edinburgh, U.K. 124 pp.
——— 1975. The significance and importance of shelterbelts in the Sudan. Sudan Sylva, 20(111), 4–6.
Salih, A.A. 1967. Meteorological report on windbreak experiment. Gezira Research Station, Wad Medani, Sudan. 4 pp.
Satchell, J.E. 1978. Ecology and environment in the United Arab Emirates. Journal of Arid Environments, 1, 201–226.
Schechter, J. 1977. The Negev life-style. Geographical Magazine, L(2), 101–102.
SETI (Société d'exploitation de l'irrigation). nd [1975]. L'irrigation localisée par rampes perforées. Compagnie nationale pour l'aménagement de la région du Bas-Rhône et du Languedoc, Nimes, France. 19 pp.
Shah, Mohammad. 1978. Salt affected soils in Pakistan. In Proceedings of the Workshop/Seminar on membrane biophysics and salt tolerance in plants. University of Agriculture, Faisalabad, Pakistan. 47–64.
Shainberg, I. 1973. Ion exchange properties of irrigated soils. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 155–164.
Shalhevet, J. 1973. Irrigation with saline water. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 263–276.
Sharma, R.C. 1973. Quality of groundwater in Saraswati Plantation, District Karnal (Haryana). Indian Forester, 99(2), 76–81.
Sheikh, M.I. 1974a. Optimum water requirement of shisham (*Dalbergia sissoo*) — Second assessment. Pakistan Journal of Forestry, 24(1), 1–9.

_____ 1974b. Afforestation in waterlogged and saline areas. Pakistan Journal of Forestry, 24(2), 186–174.
_____ 1978. Performance of poplar clones under irrigated conditions in the Punjab. Pakistan Journal of Forestry, 28(2), 120–122.
_____ 1980. Trees and agriculture go together. Pakistan Agriculture, 1980 (June–July), 30–35.
_____ 1981. Heavy pruning is injurious to poplars. Pakistan Forest Institute, Peshawar, Pakistan. Forest Research Technical Note 30, 1 p.
_____ 1982. Exotic poplars in Pakistan. Pakistan Forest Institute, Peshawar, Pakistan. 56 pp.
Sheikh, M.I., Masrur, A. 1972. Drip irrigation: A new method of irrigation developed at Pakistan Forest Institute, Peshawar. Pakistan Journal of Forestry, 22(4), 446–462.
Sheikh, M.I., Raza-ul-Haq. 1982a. Effect of spacing on the growth of *Dalbergia sissoo* (shisham). Pakistan Journal of Forestry, 32(2), 73–74.
_____ 1982b. Performance of poplars and other species in conjunction with agricultural crops. Pakistan Journal of Forestry, 32(2), 72.
Shiva, V., Shandra, S., Bandyopadhyay, J. 1982. Social forestry — No solution without the market. The Ecologist, 12(14), 158–168.
Shmueli, E. 1973. Efficient utilization of water in irrigation. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 411–423.
Simpson, E.S. 1968. Ground water hydrology of desert environments. In McGinnies, W.G., Goldman, B.J., Paylore, P., ed., Deserts of the World. University of Arizona Press, Tucson, AZ, USA. 21–92.
Singh, B. 1963. The first irrigated plantation of Rajasthan. Indian Forester, 89, 690–700.
Singh, J. 1960. Raising of irrigated plantations in the plains of Patiala and East Punjab States Unican. Proceedings of the 9th Silvicultural Conference, Dehra Dun, 1956. Part 1, 280–285.
Swaminathan, M.S. 1980. Indian forestry at the crossroads. International Tree Crops Journal, 1, 61–67.
Thirgood, J.V. 1981. Man and the Mediterranean forest: A history of resource depletion. Academic Press, Toronto, Canada. 194 pp.
Thomas, J.G., Starkey, D.A., Aslin, R.G. 1981. Drip irrigation for windbreak plantings. Cooperative and Extension Service, Kansas State University, Manhattan, KS, USA. 6 pp.
Thornthwaite, C.W., Hare, F.K. 1955. Climatic classification in forestry. Unasylva, 9, 51–59.
Tomar, O.S., Yadav, J.S.P. 1980. Effect of saline irrigation water of varying EC, SAR and RSC levels on germination and seedling growth of some forest species. Indian Journal of Forestry, 3(4), 306–314.
Troup, R.S. 1921. The silviculture of Indian trees. Clarendon Press, Oxford, U.K.
Trout, T.J. 1979. Factors affecting losses from Indus Basin irrigation channels. U.S. Agency for International Development, Washington, DC, USA. Research and Development Abstracts, 8(1), 17.
Unesco (United Nations Educational, Scientific and Cultural Organization). 1974. Influence of man on the hydrological cycle: Guidelines to policies for the safe development of land and water resources. In Status and trends in research in hydrology, 1965–74: Working group report. Unesco, Paris, France. 30–70.
UNO (United Nations Organization). 1978. The management of irrigation water in Egypt (Abstract). In Proceedings of the United Nations Water Conference, Mar del Plata, Argentina, 1977. Pergamon Press, New York, NY, USA. Volume 1, Part 4, E/Conf. 70/Abs. 19, 1788.
Urie, D.H. 1975. Nutrient and water control in intensive silviculture on sewage renovation areas. Iowa State Journal Research, 49(3), part 2, 313–317.
USDAFS (United States Department of Agriculture, Forest Service). 1980. Forestry activities and deforestation problems in developing countries. Forest Products Laboratory, USDAFS, Madison, WI, USA. Report PASA AG/TAB, 1080–1087.
Van der Zel, D.W., Wicht, C.L. 1974. Allocation of water to forestry and other users in the catchment of the Eerste River. Forestry in South Africa, 15, 47–56.
Van Hoorn, J.W., Ollat, C., Combremont, R., Novikoff, G. 1968. Irrigation with salty water in Tunisia. In Boyko, H., ed., Saline irrigation for agriculture and forestry. Junk N.V., The Hague, The Netherlands. 168–186.
Veltcamp, J.J. nd. A tentative comparison of the economics of agricultural crops and plantations of fast grown tree species (poplars) under irrigation in the Jordan Valley. FAO, Rome, Italy. Project Interim Report, 13 pp.
Vermeiren, J., Jobling, G.A. 1980. Localized irrigation — Design, installation, operation, evaluation. FAO, Rome, Italy. Irrigation and Drainage Paper 36, 198 pp.
Walker, P. 1979a. Report on the Upper Volta Micro-catchment Scheme: Draft report. Department of Agriculture and Forestry, Oxford University, Oxford, U.K. 45 pp.
_____ 1979b. Micro-catchments in Upper Volta: File note. Unit of Tropical Silviculture, Commonwealth Forestry Institute, Oxford, U.K. 11 pp.
Walter, H., Leith, H. 1967. Klimiadiagram — Weltatlas. VEB Gustav Fischer Verlag, Jena, DDR. 86 pp.
Wood, P.J. 1977. Report on forestry at Shendi, Sudan: Report to the Overseas Development Agency. Unit of Tropical Silviculture, Commonwealth Forestry Institute, Oxford, U.K. 7 pp.

Wood, P.J., Burley, J., Grainger, A. 1982. Technologies and technology systems for reforestation of degraded tropical lands: Office of Technology Assessment commissioned report. (Cited in Technologies to sustain tropical forest resources. Office of Technology Assessment, U.S. Congress, Washington, DC, USA. F.214, March 1984, 344 pp.)

Wood, P.J., Synott, T.J. 1978. Utilization of treated sewage effluent in agriculture: Report for Government of Kuwait, Ministry of Public Works. J. Taylor and Sons, Consulting Engineers, London, U.K. 61 pp.

Wood, P.J., Willens, A.F., Willens, G.A. 1975. An irrigated plantation project in Abu Dhabi. Commonwealth Forestry Review, 54(2), 139–146.

Woodman, J.N. 1971. Is there a future for irrigation in the management of forests? Paper to annual meeting, American Society of Agricultural Engineers, Washington State University, 27–30 June 1971.

——— 1973. The effect of thinning, fertilization and irrigation on intraseasonal diameter growth of Douglas fir. Paper to Northwest Scientific Association, Forestry Section, 30 March 1973.

Yadav, J.S.P. 1980. Salt affected soils and their afforestation. Indian Forester, 106(4), 259–272.

Yaron, B. 1973. Water suitability for irrigation. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 71–85.

Yaron, B., Danfors, E., Vaadia, Y., ed. 1973. Arid zone irrigation. Springer-Verlag, New York, NY, USA. 434 pp.

Yaron, B., Shainberg, I. 1973. Electrolytes and soil hydraulic conductivity. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 155–164.

Yaron, B., Vink, A.P.A. 1973. Soil survey for irrigation. In Yaron, B., Danfors, E., Vaadia, Y., ed., Arid zone irrigation. Springer-Verlag, New York, NY, USA. 203–213.